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Hardware Design for a Fixed-Wing Airborne Gravity Measurement System

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<p>This report describes the results of a hardware design study for an airborne gravity measurement system. The system is intended for use aboard a fixed-wing aircraft for measurements over oceanic areas including ice caps. Hardware for measurement of total vertical acceleration including gravity, aircraft vertical acceleration, and precise positioning is discussed; and example equipment types are specified. A data acquisition system capable of handling all measurements sources is also specified. Various aircraft operational requirements and parameters are considered.</p>				
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CONTENTS

INTRODUCTION	1
GRAVITY METER	2
LaCoste and Romberg Air/Sea Gravimeter	2
Bell Aerospace BGM-3 Gravity Meter	7
NAVIGATION	10
Global Positioning System	10
Global Positioning System and Inertial Navigation	12
ALTIMETRY	12
Radar Altimeter	12
Pressure Altimeter	17
DATA ACQUISITION SYSTEM	19
Clock	19
Computer System	20
GPS Data Requirements	20
Inertial Navigation System Requirements	21
Gravity Data Requirements	21
Altimeter Data Requirements	21
Miscellaneous Considerations	22
The NRL Data Acquisition System	22
The NRL Interface System	23
Clock and Control Subsystem	25
Memory and Control Subsystem	26
ARINC 561 Aircraft Interface	26
16/32 Bit Parallel Interface	27
Digital Sum/Average Interface	29
Power Distribution Subsystem	30
Proposed Data Acquisition Systems	30
MISCELLANEOUS AIRCRAFT CONSIDERATIONS	33
Autopilot	33
Electric Power Requirements	34
REFERENCES	36

HARDWARE DESIGN FOR A FIXED-WING AIRBORNE GRAVITY MEASUREMENT SYSTEM

INTRODUCTION

This report is a study of the hardware design for a fixed-wing airborne gravity measurement system (AGMS). It will be followed by another report on software for data acquisition and analysis. The proposed system is designed for use over open water, sea ice-covered regions, coastal areas or any regions where accurate absolute altitudes (radar or laser over a point of known altitude) are periodically obtainable. The information in this report is primarily based on experience acquired during the designing and flying of a prototype AGMS at the Naval Research Laboratory (NRL) since 1980 [1-3]. During this program we have accumulated over 800 flight hours testing various designs and modifications. Our research test bed has been NRL's P3-A Orion aircraft, and some of the information in this report is specific to that platform, although most of the proposed hardware is applicable to nearly any aircraft large enough to carry the system. The design goals are to achieve the greatest accuracy possible in the measurement and reliability of the system in the aircraft environment while minimizing its size, weight, and complexity. At the same time the proposed AGMS should be flexible enough to incorporate future advances in measurement technology. One of these advances, dynamic interferometric navigation using Global Positioning System (GPS) satellites that we discuss briefly, may make it possible to operate the system anywhere without regard to currently required periodic registration points of known altitude.

Accurate knowledge of the spatial variations of the earth's gravity field is required for several reasons. Among these are compensation of inertial guidance systems, improvements in gravity models used in orbital calculations, crustal density determination in regions of known topography, and estimation of topographic structure in oceanic areas with sparse bathymetric data. Measurement of gravity variations in oceanic areas is conventionally performed from surface ships or submarines, but the greater speed, range, and lower cost per track kilometer of fixed wing aircraft provide an attractive alternative platform. The major difficulty in performing airborne gravity measurements is the separation of the variations in gravity from the vertical accelerations of the aircraft. This problem has prevented the use of aircraft from becoming the measurement platforms of choice in the past.

Vertical acceleration of an aircraft can arise from variations in altitude above a reference surface and from the centripetal acceleration caused by motion at a constant altitude over the curved reference surface. The first type of vertical acceleration can be determined by accurate measurement of a time series of altitudes above the reference, and the second can be determined by precise navigation. The three parameters necessary for airborne-gravity measurement are; (1) total vertical acceleration, the sum of gravity and the vertical accelerations caused by the motion of the aircraft; (2) altitude, for determination of the vertical accelerations of the aircraft due to variations in altitude as well as the correction for the vertical attenuation of gravity with height; and (3) navigation, to determine the centripetal acceleration or Eötvös correction and the free-air normal gravity.

The first parameter, total vertical acceleration, is measured by a gravity meter; altitude is determined from a combination of radar and pressure altimeters; and navigation is provided by the satellite GPS. The measurement equipment, computer interfaces, data acquisition systems, and some installation and operational concerns are discussed in the following sections.

GRAVITY METER

LaCoste and Romberg Air/Sea Gravimeter

This and the next section describe some of the relative advantages and disadvantages inherent to the LaCoste-Romberg (L & R) and the Bell Aerospace gravity meters. However, it should be stated from the beginning that NRL's airborne gravity measurement system is based on the L & R air/sea type S gravity meter, and almost all of our experience is with this meter. We have recently flown a set of data flights totaling 150 h with both sensors, however the data from this experiment have not yet been reduced [4].

The L & R model S is a highly overdamped spring-type gravity sensor mounted on a three-axis gyro stabilized platform. The sensor and platform form a separate unit from the rack mounted control electronics, Fig. 1. There have been several improvements in the standard S-meter in the past few years, even the basic sensor has been changed. L & R now has a straight line meter available. This sensor uses a linear travel proof-mass rather than the pivoted beam of the earlier meters, therefore cross-coupling of horizontal to vertical acceleration is eliminated in this model. A further advantage is represented by the replacement of the delicate and critical air dampers with silicone oil dampers which improved the vibration tolerance, the resistance to shipping damage, and the sensor's life. Test mass position sensing has been simplified over the old optics system, and the analog auto reader computer has been replaced by an IBM PC. The PC not only controls spring tension and computes total correction, but performs a real-time autocorrelation off-level correction for small amounts of table level error. This would seem to be an excellent airborne gravity sensor. Many of these improvements are also available for the older beam-type sensors as well.

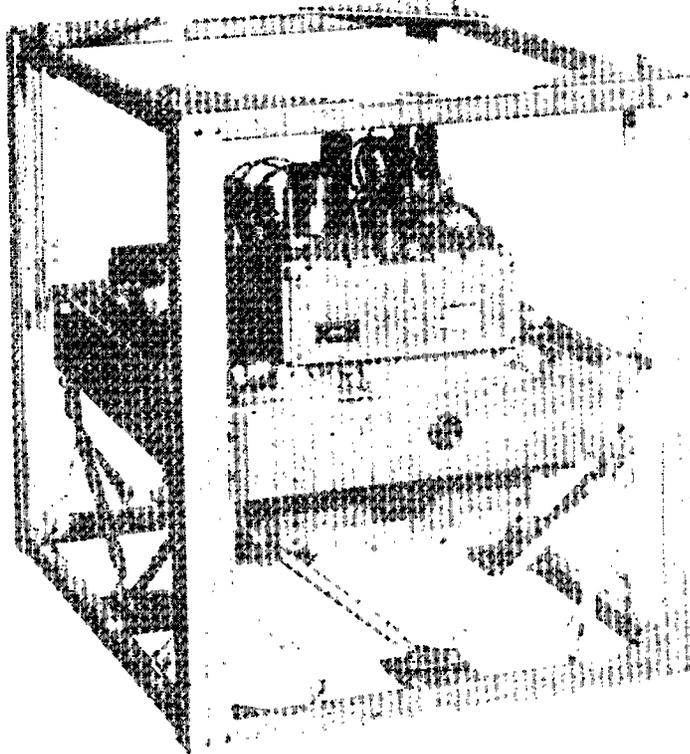


Fig. 1 — LaCoste and Romberg S type air/sea gravity sensor mounted on a 2-axis stable platform

The L & R system comes with a 400 Hz 3-phase 26 V power supply for the table gyros. This power supply weighs 29.5 kg (65 lb) and has proven unreliable in the aircraft environment. The P-3 Orion has 3-phase 400 Hz 115 V power onboard. We are currently replacing this power supply with three small stepdown transformers to save weight and increase reliability. We are also replacing the 28 V dc power supply with the onboard 28 V. L & R has redesigned some of the control electronics to combine the console junction and control boxes. If L & R can be persuaded to sell the software that drives the PC and if this code can be implemented on the data acquisition computer, the IBM PC can be eliminated as well. The resulting gravity meter has been reduced to a sensor and 3-axis platform, the junction-control box, the Inland amplifier box, 3d axis control, and the 4-channel strip chart. This configuration weighs 170 kg (375 lb) and requires 28 in. of rack space and 22 x 28 in. of floor space for the sensor/platform. The 4-channel strip chart could be eliminated if necessary, thus saving an additional 34 kg (75 lb) and 11 in. of rack space, but we have found the hard copy useful during the flight as a data monitor and afterwards for data analysis.

The leveling system for the stable platform utilizes accelerometers to precess the gyros to the local vertical. The feedback loops for this precession are designed to make each axis of the stable platform act like a damped pendulum. The period of the pendulum is selectable to 4, 18, or 84 min. The period must be long enough to average out the horizontal accelerations due to variations in heading of the aircraft. The impulse response of the PB-20E autopilot has been tested [5]. This autopilot is similar to the PB-20N used aboard A and B model P-3 Orions, except that it does not have a radar altimeter hold mode (see section Miscellaneous Aircraft Considerations, Autopilot). These tests show a return to within .8° of course within 15 s after a 4° yaw impulse is applied, Fig. 2. This implies that the 4-min period of the platform is sufficient to average out course deviations caused by wind gusts.

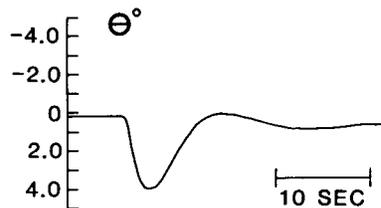


Fig. 2 — Heading response of the PB-20E autopilot to a 4° yaw impulse [5]

Also, there is a natural heading oscillation of the airframe/autopilot system. Figure 3 is a single-sided power spectral density plot for horizontal accelerations of the aircraft while flying straight and level. Flight parameters were 225 knots and 610 m (2000 ft) of altitude on a relatively calm day. Integrating this spectrum over various frequency bands and taking the square root of the integrated power produces the rms acceleration amplitude for each band (Table 1). Higher amplitude accelerations exist at short periods, particularly on gusty days; however, an analysis of the stable platform operated in the 4 min period indicates gravity measurement errors caused by the off-leveling of less than 1 mGal for sinusoidal horizontal acceleration with a magnitude of 100 Gal and a period of less than 35 s [6]. Even longer period and higher magnitude horizontal accelerations can be tolerated in the 18-min mode. The gravity measurement error caused by table leveling errors is given by:

$$\text{Error} = \frac{(\omega_0/\omega)^4}{(\omega_0/\omega)^4 + 1} \cdot (a^2/2g) \quad (1)$$

where ω_0 is the circular frequency of the stable table

ω is the circular frequency of the horizontal acceleration

a is the rms horizontal acceleration

g is the acceleration of gravity.

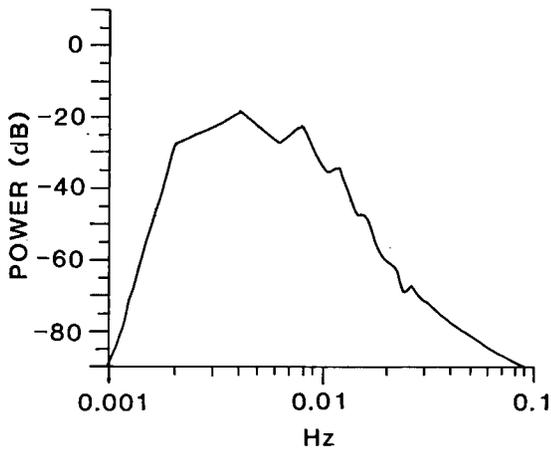


Fig. 3 — Power spectral density of P3-A horizontal accelerations during straight and level flight at 2000 ft and 225 knots. Wind conditions were calm.

Table 1 — Magnitude of Aircraft Horizontal Acceleration as a Function of Frequency

Frequency (Hz)	Period (s)	Rms Horizontal Acceleration (Gal)
.002 - .004	500 - 250	1.7
.004 - .0068	250 - 150	2.1
.0068 - .01	150 - 100	2.6
.01 - .02	100 - 50	1.6
.02 - .05	50 - 20	.6

Modeling the accelerations from the power spectrum as sinusoidal with a period midway in each frequency band we get the following gravity measurement errors caused by leveling errors in the 4 and 18-min table periods (Table 2).

Table 2 — L & R Gravimeter RMS Off-Leveling Errors Caused by Typical Aircraft Horizontal Acceleration for Stable-Table Periods of 4 and 18 min

Period (s)	Error 4 Min (mGal)	Error 18 Min (mGal)
325	1.2	< .1
200	.7	0
125	.2	0
75	0	0
35	0	0
	2.1	< .1

From experience with our airplane, we have found that the average horizontal accelerations seem to be minimized by operating the autopilot in a heading hold mode rather than having the inertial coupled to the autopilot. This may be a defect in our autopilot or it may be typical. This mode of operation requires occasional small heading corrections to stay close to the desired track across the ground. The course adjustments are typically 1° to 2° whenever the cross track error exceeds some value, for example 1 km. These course adjustments produce a horizontal acceleration of about .05 g (≈ 50 Gal) that lasts for about 10 sec. This acceleration would not cause a table leveling error if it were oscillatory in either the 4- or 18-min periods. However, the acceleration is not sinusoidal and does not average out. It is therefore necessary to switch off the accelerometer input during these small course adjustments if the table is in the 4-min mode, and probably it is better to do so even in the 18-min mode.

The technique that works best for maintaining system level and for minimizing data errors caused by leveling is to start data tracks in the 4-min period to get the platform rapidly back to level if any off-leveling has occurred during the turn. After 15 min we switch the period to 18 min. The input from the accelerometers to the feedback loops is switched off at the end of a track before starting the turn to the next track. This allows the space-stabilized gyro loops to hold the platform level for the few minutes of the turn. The horizontal accelerometer output would drive the platform off-level during the turns if this were not done. The key here is that the period of the platform is sufficiently long to average out course oscillations, and the accelerometers can be disabled during those major course changes that cannot be averaged out. We return to this point in the section on the Bell meter. It is possible to correct for most off-leveling errors that occur in the data either in postprocessing or in real time. The technique is described in Ref. 7.

One problem that arises with the L & R meter in airborne applications is the lack of dynamic range. The operators manual gives an available range of 12,000 mGal, but this does not correspond to an instantaneous figure. The dynamic range of the meter is a function of two inputs, the spring tension and the beam velocity. The spring tension provides the 12,000 mGal range but has a fairly slow response time. The instantaneous dynamic response of the meter is provided by the beam velocity, which has limited range. The actual available range varies with the character of the dynamics applied to the meter. The meter is well designed to handle large vertical accelerations that are short period and oscillatory in nature; plus or minus 1 g is tolerable if the period is 3.5 s or less, and periods of 35 s cause less than 1 mGal of error if the amplitude is reduced to .1 g [6]. These values are imposed by the limits on beam travel and are allowable because the filtering averages out the vertical accelerations. However, if the spring tension is not within approximately 100 mGal of the average, the beam velocity correction becomes invalid. This is probably due to the beam reaching terminal velocity. It is therefore possible to exceed the dynamic range of the meter for some period even with zero vertical acceleration if the spring tension is not set within 100 mGal of the gravity at altitude + Eötvös. The beam position and spring tension adjustment circuitry then begin to change the spring tension to reposition the beam near an average null. After some period of time depending on how far off the original spring tension was, the meter will be back within its dynamic range limits. We have not found this range limitation to be much of a problem in actual airborne operation of the meter. Since Eötvös correction can vary by 4000 mGal between east and west data tracks, the estimated spring tension is computed before the start of each track as a function of altitude, speed, heading, and latitude. This value is then manually dialed in during the turn to the new track.

Besides Eötvös variations, dynamic range is required to allow vertical accelerations caused by aircraft motions. The typical motion characteristics of the P-3 are quite different from those of a ship. The vertical deviations in altitude from a desired track may be divided into two interacting factors, transient gust response and the still-air autopilot/longitudinal airframe oscillation. Figure 4 shows the PB-20E vertical response to a 3.7 m (12 ft) altitude error in the constant altitude mode [5]. This test simulates the reaction of the aircraft and autopilot system to an altitude error caused by a wind gust. After 20 s the aircraft returns to within 1 ft of the correct altitude. The amplitude and period of this type of vertical acceleration should be well within the tolerance of the meter, and in practice the meter seems highly resistant to accelerations from turbulence. We have successfully operated the meter in moderate to severe turbulence, although the data begin to degrade with increasing violence of aircraft motion. The P-3 has stiff wings with very little give in response to gusts. However, the L & R meter can operate in these conditions because the high-frequency vertical accelerations are either damped or averaged out. More difficulty is presented by operations in unstable air. When large air masses are rising and falling, the altitude deviations of the aircraft can become significant enough to exceed the response of the meter. These deviations tend to cause lower magnitude accelerations than turbulence, but the duration is significantly longer so that neither the damping nor filtering is sufficient to allow continued operations.

The second type of vertical aircraft motion is the natural oscillation of the airframe/autopilot system. These are similar to the horizontal oscillations discussed above. Figure 5 is an amplitude spectral

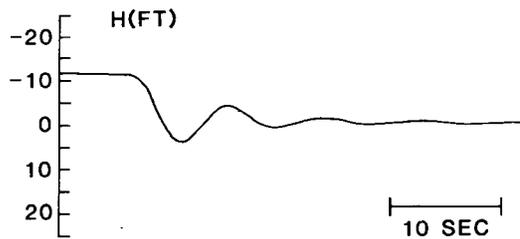


Fig. 4 — PB-20E autopilot response to a 12 ft altitude error [5]

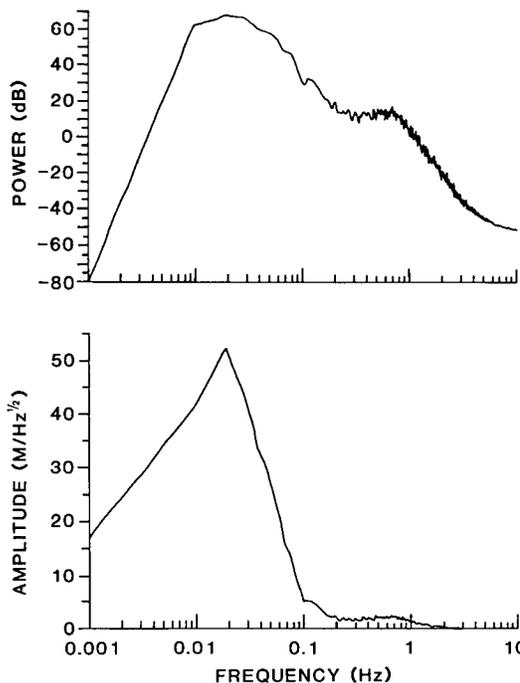


Fig. 5 — Power spectral distribution of altitude variations in a P-3A aircraft at 2000 ft and 225 knots. Altitude hold engaged, and wind conditions were turbulent

distribution of altitude for a P-3A with a PB-20N autopilot [8]. The data were taken on a turbulent flight after the passage of a cold front. The motion of the aircraft felt extreme. The spectral peak is at .02 Hz with power falling off rapidly below .01 Hz and above .03 Hz. Rms aircraft altitude deviation for the frequency band .01 to .03 Hz from this spectrum is 6.5 m. This corresponds to a vertical acceleration of about .7 Gal. After the internal filtering of the meter, approximately 200 mGal still remain. This is close to the maximum tolerable acceleration with such a long period. Days with less violent turbulence typically produce rms altitude deviations in this wave band of 2 to 3 m. Vertical motions that exceed the tolerance limits of the meter are indicated by the spring tension servo constantly racing between high and low extremes of several hundred mGal. The total correction due to beam velocity also becomes very high.

The small feature in the spectrum (Fig 5) from .1 to .2 Hz is due to the short period altitude hold loop of the autopilot. The altitude variations in this band are small, less than 1 m, but this corresponds to quite a lot of power in the vertical acceleration. This variation amounts to 50 to 100 Gal, but with such a short period that the gravity meter is unaffected. The autopilot and its extreme importance to airborne gravity measurement are discussed further in section Miscellaneous Aircraft Considerations, Autopilot.

The L & R meter puts out several channels of data. On the beam type meter the only channels necessary when the platform is level are: (1) spring tension; (2) average beam position; and (3) total cross-coupling. However, to compute off-leveling correction in realtime or in postprocessing it is also necessary to record the averaged output from the horizontal accelerometers and the vertical acceleration squared. We have also found it useful to record the unfiltered beam position so that the amount of filtering applied may be varied. The interface requirements and data rates required for the various channels of data are discussed in section Data Acquisition System.

The gravity meter must be stabilized to a constant temperature for at least 24 h before a data flight. Since it is not practical to have ground electric power onboard the aircraft at all times, it is necessary to include an independent battery power supply in the system. We have found that about 100 ampere hours (A-h) of capacity is sufficient to support the meter for 48 h between flights, as long as the ambient temperature is above 10° C. Colder conditions require more capacity. Aircraft batteries must not produce hydrogen while charging unless vented overboard, and they must be resistant to spilling acid. We have found that gel cells meet both requirements for the aircraft environment. 100 A-h can be provided by four batteries with a total weight of 29.5 kg (65 lb). The batteries are recharged in flight by an onboard charging system.

The gravity meter and stable table should be installed on the center line of the aircraft, close to the centers of pitch, roll, and yaw if possible. This minimizes the ramp accelerations caused by motions around these axes. The axis with the least amount of motion and hence of the least importance for this effect is pitch. Provision for clamping the gimbals within the supporting frame must also be made during installation. This is to meet the safety requirement for a ditching or hard landing situation.

Bell Aerospace BGM-3 Gravity Meter

The Bell BGM-3 gravity meter is based on the Bell Model XI inertial grade accelerometer. The accelerometer is mounted inside two concentric ovens for temperature control, and these in turn are mounted on a two-axis stabilized platform. The stable table can be rack mounted, and in this configuration the total system with the exception of the data acquisition computer will fit in one standard 19 in. aircraft rack. The total weight, including the rack but without the batteries, is 122.9 kg (271 lb). The design of the meter and supporting electronics is modern and compact and seems to be well suited for aircraft use. However, there are problems to be overcome in the use of the standard BGM-3 as currently supplied by Bell. Our experience with the meter is somewhat limited compared to the L & R system. We have flown the BGM-3 for about 150-h spread over two months. This experiment was performed very recently (Feb-Mar 1986), and while the data are not yet fully reduced, we have acquired a feel for operating the system in the aircraft.

The stable platform of the BGM-3 is operated somewhat differently than that of the L & R. The fundamental period of the table is 2.2 min as opposed to the 4 or 18 min of the L & R platform. While such a short period allows the table to quickly level after a turn, it appears to be too short for the typical horizontal motion characteristics of the P-3. The error due to horizontal acceleration in the BGM-3 is given by

$$\text{error} = \frac{a^2}{2g} \cdot \frac{1}{1 + \left(\frac{\omega_0}{\omega_n}\right)^4} \quad (2)$$

where α is the rms horizontal acceleration

ω_n is the circular frequency of the acceleration

ω_0 is the circular frequency of the stable table, and

g is the acceleration due to gravity

Referring again to the power spectral distribution of horizontal accelerations (Fig. 3) and the integrated horizontal accelerations described in the previous section, the error resulted from the off-leveling in the BGM-3 is shown in Table 3:

Table 3 — BGM-3 Gravitmeter
RMS Off-Leveling Errors Due to Typical
Aircraft Horizontal Accelerations

Period (s)	Error (mGal)
325	1.5
200	1.9
125	1.5
75	.1
35	0
	5.0 Total

This is almost 2.5 times the error in the LaCoste system operated in the 4-min mode. The L & R system has essentially no error attributable to horizontal accelerations in the 18-min mode, but it may lose data at the start of a track. The difficulty is caused by the fundamental difference between the characteristics of shipboard and aircraft motion. The magnitude of an aircraft's horizontal acceleration tends to be smaller than that of ships, however at considerably lower frequencies. Figure 6 [9] shows the allowable range of peak-to-peak horizontal acceleration as a function of frequency that will result in a 1 mGal error or less. Accelerations with rms magnitudes greater than 1 Gal must have periods shorter than 150 s to stay within the shaded area of the graph. It is probably impossible to fly any sort of aircraft/autopilot combination to this degree of precision. The table period must therefore be increased if the meter is to be operated aboard an aircraft.

It may be possible to correct the data for off-leveling errors as in the case of the L & R meter, but it is not obvious how this may be accomplished. This is because the platform is erected to what Bell terms the effective level rather than the true local vertical. This is the position that, on the average, causes the negative and positive off-level errors to cancel out. We know of no way to determine in postprocessing the relation of effective level to the local vertical if the accelerometer loop voltage saturates. We found that during flight this voltage did indeed frequently saturate because of the aircraft horizontal accelerations. This happened, in particular, when we applied a 1° to 3° course correction as described in the previous section. Because the accelerometer input cannot be switched out of the leveling loop, off-leveling error is inevitable. Modeling the horizontal acceleration as sinusoidal with rms magnitude of .05 g and period of 20 s, the off-leveling error during the course correction is about 160 mGal. This analysis is conservative in that the horizontal acceleration used to get back on the desired track is not oscillatory. The character is more impulse like. The effect of these small course changes then is to lose data for about 1 to 2 min each time. The L & R eliminates this problem by allowing the accelerometer input to the gyro loop to be shut off during the turn.

The BGM-3 converts the accelerometer current that is the measure of acceleration to a pulse rate proportional to acceleration. These pulses must then be counted for some period of time, and the rate can therefore be determined. The scaling of the pulse rate converter is 5 mGal/pps, thus implying the need to count for at least 5 s to achieve a resolution of 1 mGal. To minimize the overall system error we would like to hold this error to some fraction of an mGal. The counting period required is then 15 to 20 s, which is a spatial sampling rate of one data point every 2 or 3 km at aircraft speeds. It would be desirable to modify the meter to have a higher resolution scaling factor in the pulse rate converter. Our current measurement systems and data reduction schemes only allow resolution of gravity anomalies with wavelengths of 5 km or greater. We hope to increase this resolution in the future by improving navigation, altimetry, and processing. This will also require that the gravity meter be capable of similar high resolution. One way to increase the resolution of the BGM-3 would be to reduce the

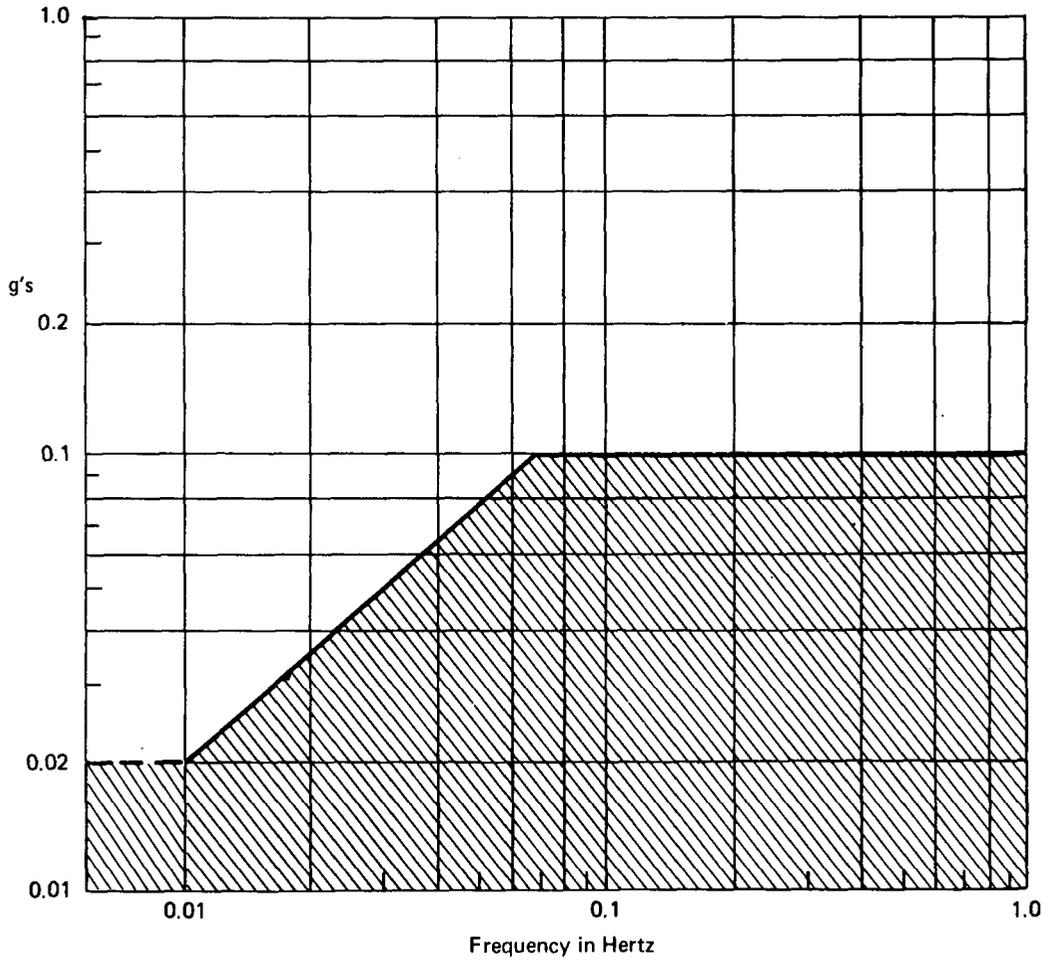
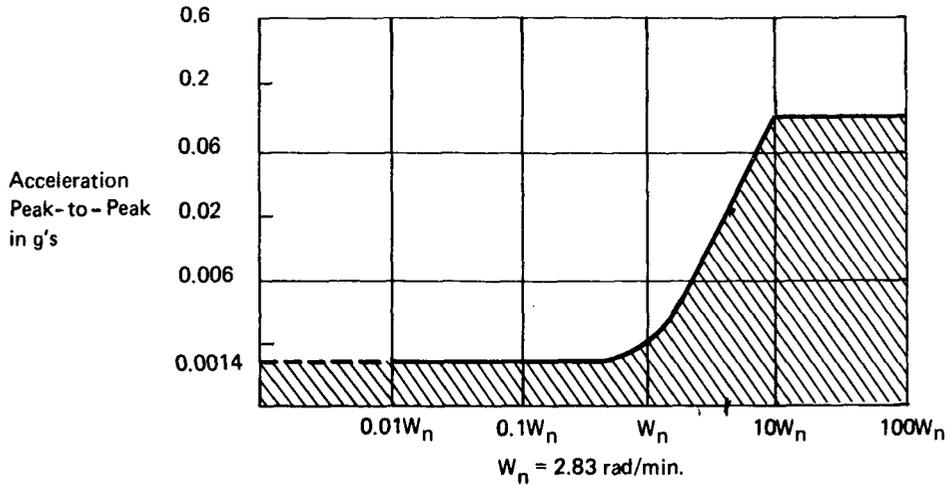


Fig. 6 — Allowable horizontal acceleration to produce less than 1 mGal off-leveling error in the BGM-3 (BGM-3 operator's manual)

dynamic range of the system from its current range of 200 Gal. This would preclude operation in turbulent conditions, however, and negate one of the advantages of the Bell system. Hopefully the pulse rate converter could be redesigned at the factory to increase the resolution without reducing the dynamic range.

The BGM-3 then requires three modifications to make it suitable as an airborne system. (1) The table period must be increased. Preferably the period should be selectable for different flight conditions. A more complicated but elegant solution would be to include high-quality navigation information into the table-leveling solution. This would allow the meter to be kept level even through turns. (2) If the table period is increased, a switch to disable the accelerometers must be included, otherwise the increased period will cause considerable data loss at the start of tracks while the table is coming back to level. If the leveling problem is solved by including navigation as mentioned above, this modification will not be necessary. (3) The scale factor on the pulse rate converter should be increased to something like 2 mGal/pps to allow greater sampling density along track. With these modifications the BGM-3 should prove to be an excellent airborne gravity meter.

The data from the BGM-3 can be read from the data buffer box by a General Purpose Input Output (GPIO) interface card. The data stream is a simple string of 60 1-s pulse-counts followed by a status word. The data rate is thus very low and easy to handle. Capability exists to input serial RS 232 navigation data to the navigation buffer board. This in conjunction with a Hewlett-Packard 9825A calculator provides real time Eötvös and latitude corrections.

Like the L & R meter, the BGM-3 must be kept heated. In fact it is even more critical that the meter not cool down during a survey operation. The power between flights can be supplied by gel cell batteries. However, the BGM-3 seems to draw about twice as much current as the L & R. Approximately 200 A-h capacity should be sufficient to provide 48 h down time between flights. This is roughly 59 kg (130 lb) of batteries.

NAVIGATION

Global Positioning System

The only worldwide navigation system currently available that is sufficiently accurate for determining Eötvös correction in airborne gravimetry is the Global Positioning System (GPS). When the full set of 18 satellites is in place, the system will provide 24 h/day real-time navigation anywhere in the world. Unfortunately, the standard positioning service provided by the C/A code will not be sufficiently accurate for successful airborne operation once it is degraded to the planned 100-m accuracy. The AGMS requires the use of the P-code which provides unaided positions accurate to 14 m SEP (spherical error probable) with four satellites and a position dilution of position (PDOP) of 3.0 or less. Under the same conditions, velocities are accurate to .15 m/s with 50% probability. Differential operation of a second receiver at a fixed location within 500 km of the mobile set can reduce these errors to 4 m and .08 m/s respectively [10]. Until the full constellation of satellites is available, it is possible to use an atomic frequency source and/or altitude aiding in the position solution to reduce the required number of satellites to 3 or 2. In this case there is 10 to 12 h of coverage over most of the world with even the satellites available at this time (mid 1986).

Currently the best available GPS receiver for the AGMS appears to be the Texas Instruments (TI) TI-4100. This is a two-frequency, multiplexed single channel, P-code receiver [11]. The dual frequency (L1/L2) capability allows an accurate measure of the tropospheric-ionospheric signal delay. Single frequency receivers must use modeled delays that produce additional errors. The TI-4100 is referred to as a multiplexed receiver because, although the set scans from satellite to satellite and receives data from each sequentially, the dwell time on each is very short (a few milliseconds). This procedure is a compromise between the expense, complexity, and interchannel biases inherent in multichannel receivers and the low dynamic capability of typical sequential sampling receivers. As mentioned above, the ability to utilize the P-code is vital because of the increased accuracy over the standard positioning service. The only other P code capable receivers available at this time are made by

Rockwell Collins. Little operational data on these receivers is available as they are just now being introduced. On the other hand, a large body of experience exists for the TI sets. The Defense Mapping Agency and the National Oceanographic and Atmospheric Agency have been operating many of these receivers for the past 2 years.

NRL has had considerable flight experience with the prototype TI HDUE GPS receiver as well as several data flights with the TI-4100. The receiver seems well suited for aircraft applications; it is compact and light, requiring only 9 in. of rack space in a conventional 19 in. rack and weighing 24 kg (53 lb). Power requirements are 110 W of 28 Vdc from the aircraft supply. The unit has been ruggedized for vibration to MIL STD 810D, a helicopter standard. Temperature tolerance is -20° to 50° C. The antenna/preamp unit is low profile and relatively easy to mount on a P-3 aircraft. We have designed a base plate assembly for mounting to the sextant port that is about midway on the fuselage top between the cockpit and the vertical stabilizer (Fig. 7). This location seems to minimize the shadowing of the antenna by the empennage and the wings during turns.

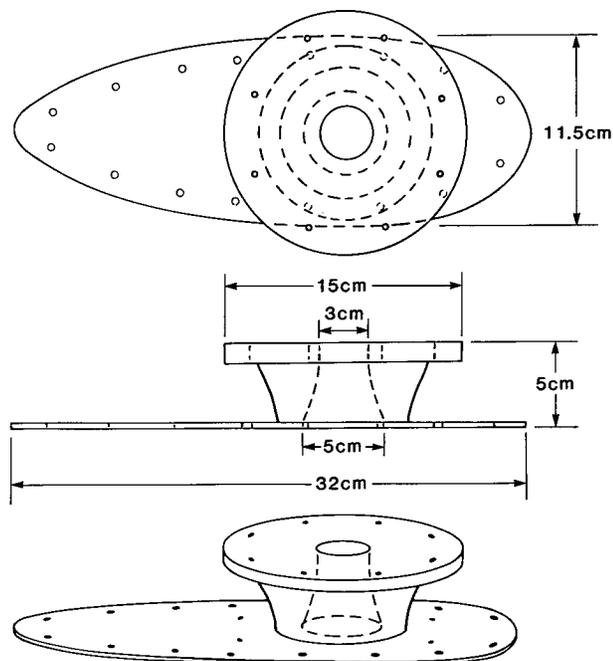


Fig. 7 — Base plate assembly to mount the TI-001 GPS antenna to the sextant port of the P-3A

The TI-4100 has a built-in connector for input from an atomic clock (cesium or rubidium) and the software to provide navigation solutions from three (clock-aided) or two (clock and altitude-aided) satellites. The standard data input and output display is a hand-held computer display unit (CDU). We recommend use of the standard RS-232 interface port to input data and instructions from the data acquisition computer system rather than by means of the CDU. The operator, as we have experienced aboard the aircraft, invariably drops and breaks the CDU, thus disabling the GPS. The CDU should be reserved as a backup input and display unit.

The ability to measure and record carrier cycle and fractional cycle counts is another feature of the TI-4100. This allows the unit to be used in an interferometer mode along with a stationary ground-based unit. See Ref. 12 for a good treatment of GPS interferometry. The first test of dynamic GPS interferometric navigation aboard an aircraft was recently performed [13]. RMS positional errors of less than 10 cm were achieved over baselines of some tens of kilometers. This technique offers great hope for the future for both navigation and altimetry. Three-dimensional positioning with this degree of

accuracy could eliminate the periodic measurement of absolute altitude above a reference by radar now required to update the pressure altitude. This would permit system operation over topographically unsurveyed continental areas or mountainous regions.

Global Positioning System and Inertial Navigation

Certain situations make advantageous the combination of a high-quality inertial navigation system (INS), such as the Honeywell SPN/GEANS, with a GPS. The NRL aircraft are equipped with the somewhat less accurate Litton LTN-72. The INS can be used to improve the performance of an integrated navigation system during periods of poor GPS performance. These periods primarily occur because of the loss of satellites and poor satellite health or geometry. Satellites can be lost during turns or from temporary shading by the aircraft tail or wing; also they can be manually dropped out while switching to a new constellation. The navigation solution from an unaided GPS is degraded during these periods. A Kalman filter utilizing both the INS and the GPS data can prevent the solution accuracy from deteriorating during the relatively short periods described above but in general will not reduce the rms errors experienced during periods of "good" (low PDOP) GPS coverage. A relatively simple Kalman filter with a minimum number of states would probably be sufficient for this task and could be implemented in real time. Another advantage of this approach is that the output of the filter can be used to drive the aircraft autopilot through an appropriate interface. This procedure would allow a predetermined set of data tracks to be flown with maximum fidelity. Flying the plane with a minimum of course changes is always important to reduce the variation in Eötvös effect. However, it is also important to be able to fly close to the desired track, particularly in the case of close line spacings or duplicate tracks.

It is necessary to postprocess the data for the most accurate possible navigation. The data from the INS can be used to aid the GPS in a differential or interferometric mode. Simulations have demonstrated INS-aided differential GPS rms errors of .75 and .35 m for aided-carrier-phase difference GPS over 100 km baselines [14]. The improvement over unaided interferometric navigation comes primarily through the increased ability to detect and correct for integral cycle slips. It would therefore be highly advantageous to record the data from a good quality INS as well as the GPS for both real-time and postprocessed navigation.

ALTIMETRY

Radar Altimeter

The primary source of absolute altitudes for computation of the vertical acceleration of the aircraft and for the height correction (vertical attenuation of the gravity field) while flying over water, is a radar designed to measure range very accurately. A pulse radar with a very narrow pulse width and a high repetition rate can measure range to an accuracy of better than 0.3 m (1 ft). The measurement accuracy of range for a pulse radar using the leading edge of the transmitting and receiving pulses to measure the travel time distance can be shown to equal [15]

$$\delta T_R = \left(\frac{\tau}{2B \cdot SN} \right)^{1/2} \quad (3)$$

where δT_R is the error in the time measurement
 τ is the pulse width
 B is the receiver bandwidth, and
 SN is the signal to noise ratio of the detected signal.

For a 3 ns pulse width, a 1 GHz bandwidth, and a desired accuracy of 0.5 ns, the signal-to-noise ratio must be 8 dB minimum. To determine the power requirements of the system, one first must consider the scattering characteristics of the sea surface. The reflectivity of the sea surface at microwave

frequencies has been studied by many investigators, for example Ref. 16. In radar studies, target characteristics are defined by the effective radar cross section (RCS) of the irradiated surface. The RCS of a target is a sensitive function of its orientation and its dimensions in units of wavelength. By definition, the cross section of the object scatters equally in all directions and is equal to its projected area. In studies of echoes from land and sea, a quantity was introduced that defines the RCS per unit area of surface. This quantity is the normalized RCS, σ_0 . The RCS is equal to σ_0 times A, where A is the effective area of a smooth surface of the irradiated cell. The studies indicate that at microwave frequencies of about 10 GHz, σ_0 measured at grazing angles of $90^\circ \pm 10^\circ$ is equal to about one and is constant for large variations in sea state and for various combinations of signal polarizations.

For narrow pulse systems the irradiated area is usually pulse-limited. A wave front produced by a narrow pulse system first strikes the surface as a small spot and expands outwardly. The irradiated area increases until the trailing edge strikes the surface. As the wave front continues, a hole develops and an expanding annulus is created. The angle from nadir subtended by the edge of the illuminated area at the time the trailing edge of the wave strikes the surface is given by Ref. 17 as

$$\Theta_p = \left(\frac{c\tau}{H} \right)^{1/2} \quad (4)$$

where Θ_p is the half angular width of the footprint
 c is the speed of light, and
 H is the vertical range.

The radius of the circle illuminated is given by Ref. 17 as

$$r = H \sin \Theta_p \approx (Hc\tau)^{1/2} \quad (5)$$

and the area is

$$A \approx \pi Hc\tau. \quad (6)$$

Therefore the area increases by the first power of range. In radar measurements, the echo power, S , received is [15].

$$S = \left(\frac{P_T G_T}{4\pi H^2} \right) \cdot \left(\frac{\sigma}{4\pi H^2} \right) \cdot \left(\frac{G_R \lambda^2}{4\pi} \right) \quad (7)$$

where P is the power transmitted
 G_T is the gain of the transmitting antenna
 G_R is the gain of the receiving antenna
 σ is the radar cross section, and
 λ is the wavelength of the signal.

The first factor in Eq. (7) defines the power density (w/m) illuminating a target at a distance H from the antenna (i.e., isotropic radiator \times transmitting antenna gain). The second factor describes the effective echo area and its reradiation of the reflected power. The third factor defines the effective receiving area of the antenna. For narrow-pulse-width systems, where the 3 dB antenna beamwidth is greater than the beamwidth subtended by the effective irradiated area, the echo power is given by

$$S = \frac{P_T G^2 \lambda^2 c \tau}{256 \pi^2 H^3} \quad (8)$$

where the $G_T = G_R$ and each antenna is assumed to be 50% efficient.

For aircraft operations a narrow beam antenna is desirable because the return power increases and in turn improves the received signal-to-noise ratio and allows operations at greater altitudes. The beam must also be wide enough to maintain a vertical component with moderate variations in the orientation of the aircraft. Experience with NRL's P-3 aircraft using a 9° beam antenna resulted in very low data loss caused by beam displacement from the nadir. The maximum effective area irradiated by a narrow pulse system defines a maximum beamwidth. For beamwidths smaller than this value, the system is said to be beamwidth-limited. Using the above equation for a range of 300 m, and a pulse width of 3 ns results in an effective irradiated circular area of 848 m² with a radius of 16.4 m, giving an antenna beam width of about 6°. Table 4 shows the beamwidth for a variety of altitudes.

Table 4 — Radar Altimeter Beam Width as a Function of Altitude

Altitude (m)	Coverage Area (m ²)	Beamwidth (deg)
300	848	6.2
600	1698	4.4
1200	3396	3.1
2400	6792	2.2
4800	13584	1.6
9600	27621	1.1

The noise power generated by a receiver that has a noise figure of 3.0 dB is given by [15]

$$N = kT_0BF \tag{9}$$

where $k = 1.38 \times 10^{-23}$ is Boltzman's constant

$\beta = 1$ Ghz is the bandwidth

$T_0 = 290$ K

$F = 3$ dB is the noise figure

and is equal to 8×10^{-12} W = -81 dBm.

As previously noted, to obtain an accuracy of 0.5 ns, the receiver input signal-to-noise ratio must be greater than 8 dB. Therefore the received power must be a minimum of -73 dBm or 5×10^{-11} W. Table 5 lists the maximum range possible meeting the above requirements for a variety of transmitting powers. Figure 8 is a block diagram of a system that can operate over the range stated in Table 5.

Table 5 — Radar Altimeter Range as a Function of Transmitter Power

Power (T) (W)	H max (m)
1.0	966
10.0	2080
100.0	4483
200.0	5648
400.0	7072
800.0	8910
1000.0	9660

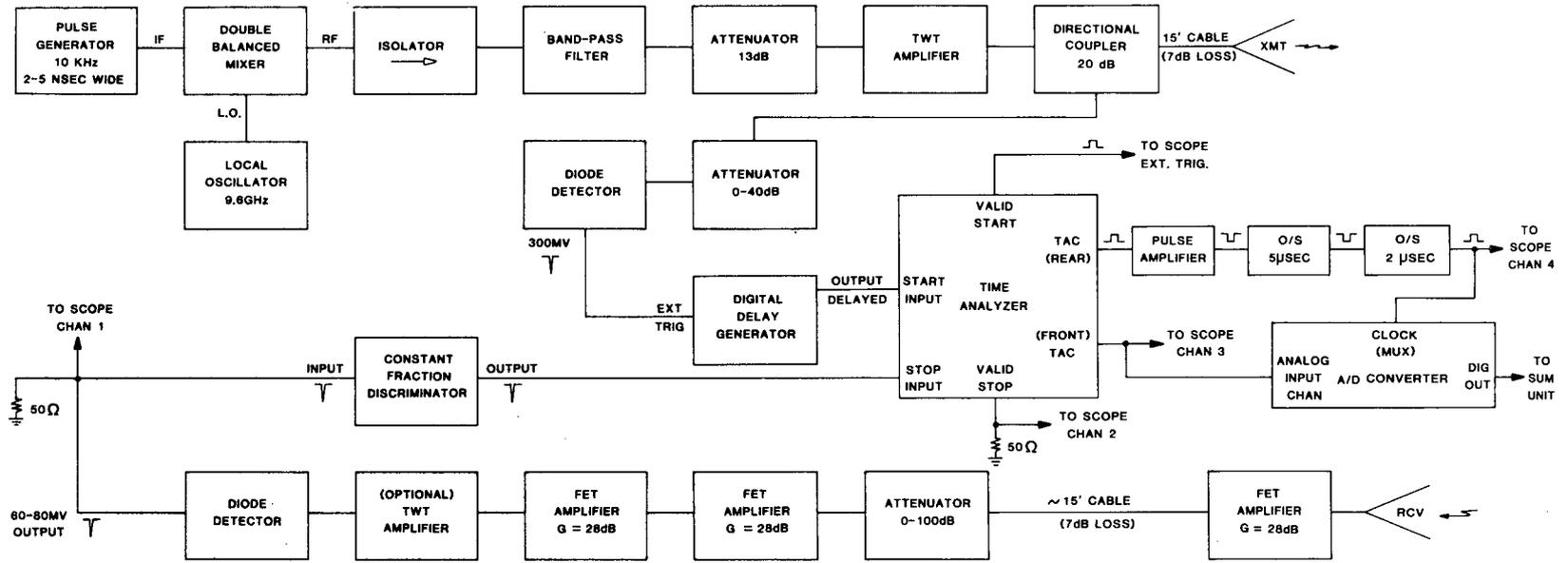


Fig. 8 — High-precision radar altimer block diagram

For radar systems that must operate with transmitting powers greater than 400 W with very narrow pulse widths, pulse compression techniques should be considered. These techniques allow generation of high transmitting powers with wide pulse width modulation, easily obtained with high-power tubes. The compression technique effectively narrows the final pulse width of the signal [15].

The frequency of operation of a radar ranging system is dictated by the availability of components with the necessary specifications and the size of the antennas that can be reasonably operated. The higher the antenna gain the larger its size and the narrower its 1/2 power beam width. The beam width must be selected sufficiently wide to eliminate the need for active pointing stabilization. The antennas used by NRL are electromagnetic horn radiators with a gain of 26 dB and a 1/2 power beamwidth of 9°. The throat dimension of each horn is 16 × 23 cm wide and 74 cm tall. Atmospheric attenuation as a function of frequency, owing to rain, clouds, fog, etc., is minimal because of the short propagation distances [18].

The following text describes a highly accurate short-pulse radar altimeter that can be built from off-the-shelf components (Fig. 8). The major sections of the altimeter are: (1) pulse generator, (2) transmitter amplifier, (3) receiver amplifier, (4) detector, and (5) timing circuitry.

The required narrow pulse of radio frequency (RF) for the transmitter is generated by using a double-balanced mixer as an upconverter where the carrier is a local oscillator (LO) signal (≈ 9 GHz) and the modulating signal is a pulse at the intermediate frequency (IF) port. The result is a pulse-modulated signal at the RF port of the mixer. The double-balanced mixer must have sufficient isolation between the LO and RF ports to give a high signal-to-noise ratio pulse. Three parameters are important when specifying the balanced mixer. The first is the IF bandwidth that should be from dc to a minimum of 1 GHz so that a narrow pulse of 3 ns can be used. The second parameter is the conversion loss that indicates the level of the upconverted signal referenced to the level of the LO signal. The third parameter is the isolation between the LO and RF ports that gives the level of the LO feedthrough when the pulse is not present. The difference between the conversion loss and isolation indicates the signal-to-noise ratio of the pulse-modulated signal at the RF port. This ratio should be a minimum of 30 dB.

The level of the local oscillator is dictated by the input requirements of the mixer, usually +10 dBm. With a conversion loss of 6 dB, the output signal is at a level of +3 dBm. The signal is then fed to a power amplifier to generate the final transmitting signal. The power amplifier should be located very close to the antenna to minimize cable losses. The gain of a traveling wave tube (TWT) amplifier is usually very high and will probably require that the mixer signal be attenuated. Therefore, sending this signal over long lines to the TWT amplifier, which may be located in a radome, will not decrease the power at the antenna as would be if the cable loss occurred after the TWT amplifier. A portion of the transmitting signal is then sampled with the use of a directional coupler and is used as the start pulse for the measurement of time. An electrically-controlled attenuator is included after the directional coupler to allow testing of the system on the ground without saturation occurring at the receiver input.

The received signal is amplified by an RF amplifier located at the antenna to minimize input signal loss caused by cable attenuation. An attenuator is then included after the amplifier to allow for fine adjustments of the signal level during both preflight and flight operations. Additional amplification is also included to produce a signal of sufficient amplitude at the detector output to meet the input requirements of the Constant-Fraction Discriminator. An important specification for the diode detector is its video bandwidth. Very low shunt capacity is necessary so that it can respond to narrow pulses. Its sensitivity, voltage output vs power input, is also a very important consideration and should be as high as possible.

The Constant-Fraction Discriminator (e.g., Canberra Model 1428A) has a large input dynamic range, usually from -5 mV to -5.0 V. A threshold adjustment can be set to produce an output pulse

whenever the threshold is exceeded. The unit may be operated in one of three different modes. The first is the Leading-Edge Mode and produces an output pulse whenever the threshold is exceeded. The second is the Constant-Fraction Mode and can be adjusted to produce an output pulse when the level reaches 75% of peak value. The third is the Constant-Fraction Slow-Rise-Time Mode and is essentially the same as the second mode but optimized to operate with slow rise time signals. These last two modes are designed to minimize the jitter or walk associated with time changes in the threshold trigger point when changes in amplitude occur.

The output of the constant fraction discriminator is fed to the stop input of a time analyzer. The time analyzer (e.g., Canberra Model 2043) generates an output pulse level that is proportional to the time difference between the start and stop pulses. The maximum output peak level is +10 V. This corresponds to the maximum time difference selected by the time range and multiplier controls. The smaller the time range selected for the 0 to +10 V output pulse range, the higher the measurement resolution.

To obtain higher measurement resolution, a digital delay generator (e.g., Berkely Nucleonics Model 7030A) is included between the diode detector for the transmitted pulse and the start input of the time analyzer. A delay is selected where the remaining delay is small and can be analyzed by choosing a short analysis range on the time analyzer. The peak of the output pulse is very flat and extends for a period of 80 μ s. This allows time to generate a sampling strobe for an A/D converter so that the peak level can be digitized.

The pulse repetition frequency (PRF) of the radar is selected as high as practicable to allow averaging a large number of samples. A PRF of 10 kHz was selected for this application. The strobing of the output pulse from the time analyzer is digitally delayed to allow the pulse sufficient time to stabilize. A nominal required altitude sampling rate of 100 Hz permits averaging 100 pulses per sample. This reduces white noise error in the averaged altitudes to 1/10 of the rms error in each individual pulse.

Pressure Altimeter

Pressure altimetry provides altitudes over surfaces other than water or smooth ice. Pressure measurements are related to absolute altitudes when compared with the radar altitudes at reference points of known altitude. These points may be over bodies of water such as rivers, lakes, or ice leads, or over surveyed positions such as roads or airports. Periodic absolute altitudes from the radar are used to determine a sea level pressure curve under the aircraft track. This curve is used to calculate absolute altitudes from the pressure measurements.

It is difficult to measure a precise static pressure from a moving aircraft, since turbulence and bow shock cause interference close to the plane. To minimize these sources of error and achieve the most accurate possible pressure altitude, we mount a highly sensitive absolute pressure transducer on a 3.5-m boom that is attached to a specially strengthened nose radome (Fig. 9(a)). The boom assembly inserts the static pressure port ahead of the bow shock and turbulence produced by the aircraft. The boom and modified radome were designed by the Technical Support Division of the Patuxent Naval Air Test Center. As with all structural modifications to Navy aircraft the engineering data and plans required approval by NAVAIR. The design, approval, and production of this structure represent a significant effort that required several months to complete.

The pressure transducer in the NRL system is a Rosemount 1201F1A3A1B; it is accurate over a range of 800 to 1100 mb to .3 mb or roughly 2.5 m. The resolution is better than 20 cm at sea level. The lower limit on pressure of 800 mb allows operation at altitudes up to approximately 5 km (16000 ft). This model was selected in preference to the one with a range of 0 to 1100 mb because the resolution and accuracy are nearly four times better. The transducer is mounted in a small housing about 2m out on the boom to reduce the plumbing length forward to the static pressure port to a minimum. This increases the high-frequency response of the system to pressure fluctuations. The transducer operates

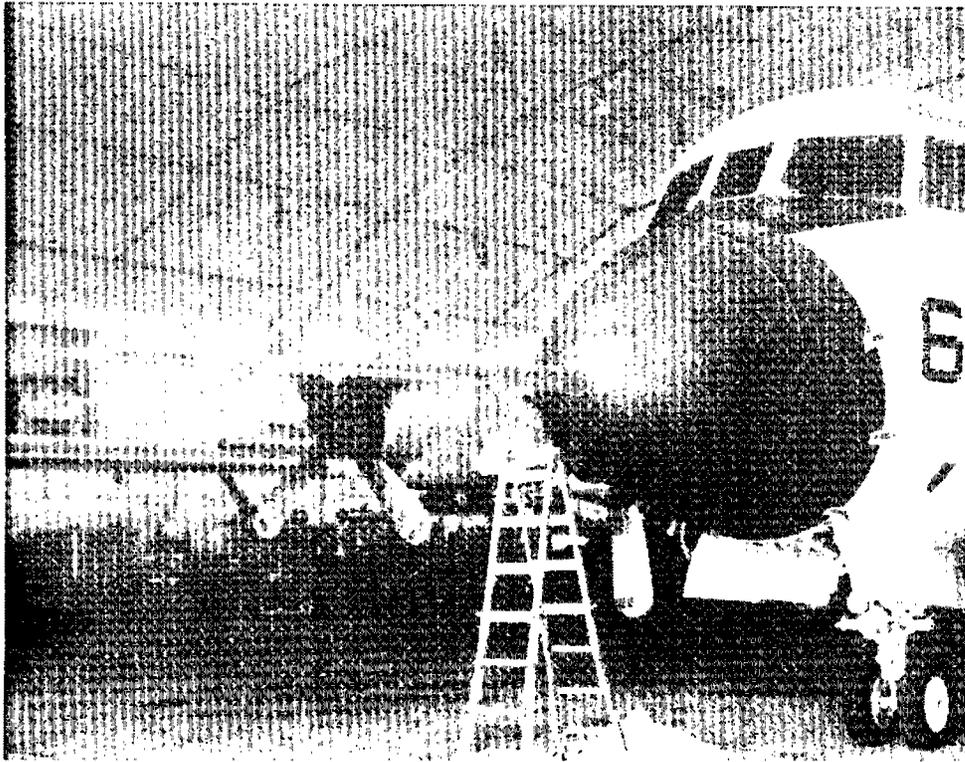


Fig. 9(a) — Boom for the pressure altimeter mounted on the nose radome

on ± 15 Vdc. Data output is an analog voltage ranging from 0 to 10 V with a linear conversion of voltage to pressure (0 V = 800 mb, 10 V = 1100 mb). The conversion from pressure to altitude is given by:

$$H = \frac{P_0^n - (P - .3)^n}{8.42288 \times 10^{-5}} \quad (10)$$

where H is the altitude in meters
 P_0 is the sea level pressure in millibars (mb) (altimeter setting)
 P is the transducer pressure in mb
 $n = .190284$.

Therefore, sea level pressure must be known to accurately determine altitude.

The actual static pressure port is on a pivoting probe (Fig. 9(b)) on the forward end of the boom. The probe is vaned, and it pivots in two axes to ensure that the static port is held parallel to the slipstream at all times. If the probe did not weathervane into the wind, the sensor would be exposed to ram air from the pitch and yaw of the aircraft. Pitch and yaw sensors are also installed on the boom behind the probe. We have recently discovered that the pressure probe will have to be redesigned to include provisions for anti-icing. While operating in cloudy conditions over Antarctica, we experienced difficulty with ice accumulation on both the probe and the vanes. When this occurs the aerodynamics of the probe are spoiled even if the static port is not blocked. Ice chunks breaking loose from the probe and boom also seemed to be somewhat hazardous.

Considerable internal bracing and structure is required inside the nose radome. This metal bracing blocks the forward weather radar antenna over most of its pattern. We replaced the standard Navy radar with a Bendix color weather radar. This has a 10 in. diameter flat plate antenna that looks forward through a hole in the lower portion of the bracing plate (Fig. 10). The replacement of the radar had several additional benefits. The new unit is more than 68 kg (159 lb) lighter than the old one. It

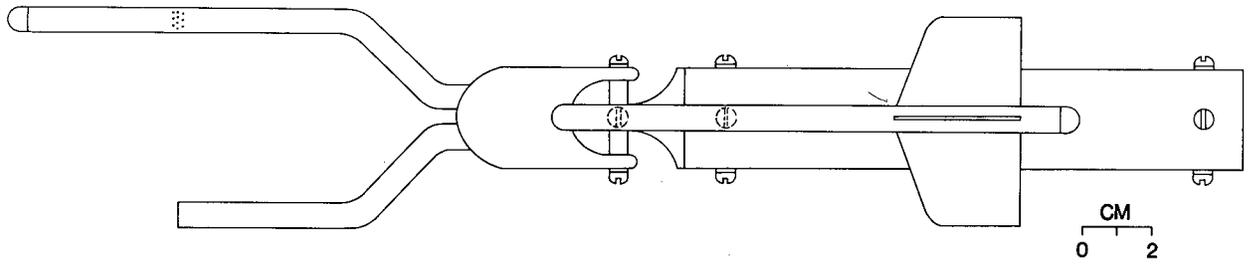


Fig. 9(b) — Details of static pressure probe

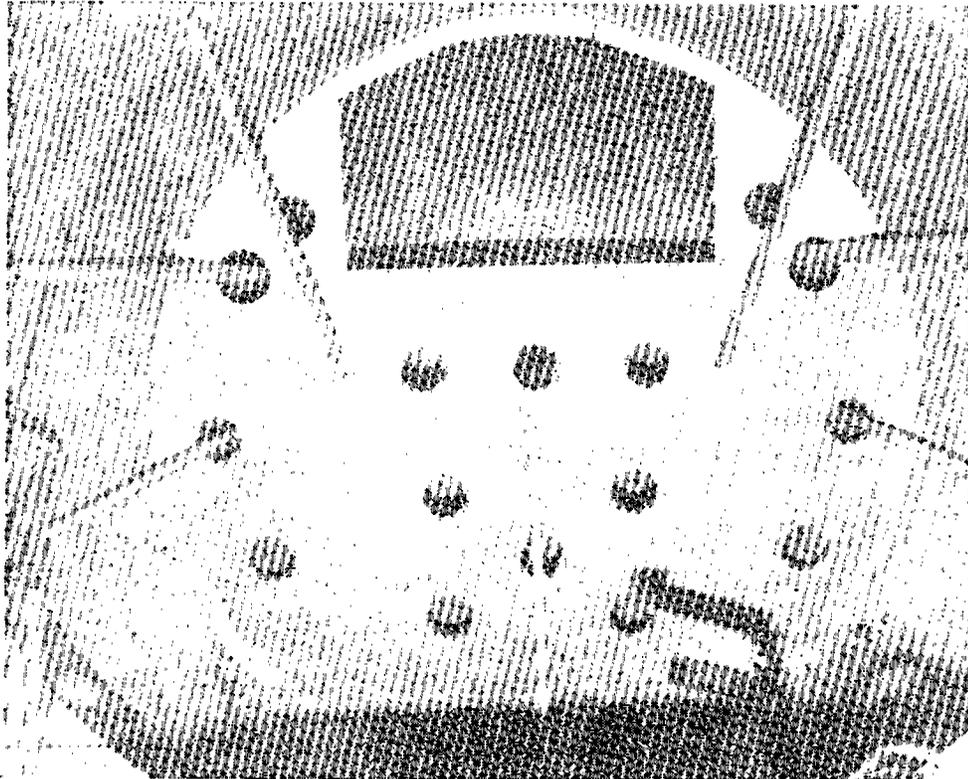


Fig. 10 — Radome bracing for the pressure sensor boom

also appears to work better in defining the strength of precipitation. The radar display is compact enough to be mounted on the cockpit, thus giving the pilots better access to weather information. It also can be interfaced with our aircraft Litton-72 inertial navigation systems to display navigation information and checklists.

DATA ACQUISITION SYSTEM

Clock

Data from each of the subsystems (gravity, altimetry, and navigation) is collected by separate, asynchronous programs. It is important to be able to tie the various types of data together by time of collection. This is done by carefully tagging each input record with the time; then, later processing the data can be correlated and interpolated to the same time base for the final calculation of gravity. To do this it is useful to have one clock for all of the subsystems.

First it is necessary to have an accurate frequency standard. For most of the subsystems a precision of one part in 10^9 is sufficient for the duration of one flight. However, the TI-4100 GPS receiver can use a frequency with a precision of one part in 10^{11} to get accurate fixes with less than four satellites visible. This effectively extends the hours of coverage of GPS navigation until such time as the complete suite of GPS satellites is launched. This time accuracy is available in a rubidium standard oscillator such as the Hewlett-Packard HP5065. The unit has output frequencies of 5 MHz, 1 MHz, and 100 kHz. These can be divided down to rates appropriate for the various subsystems of the gravity system. There is one cautionary note on the use of high-precision oscillators such as the HP5065; they generally have an oven that must reach a stable temperature before the oscillator operates correctly. It is best to be able to keep the oscillator running on ac power or on its battery backup at all times. To do this either the battery must be kept in operation on the aircraft or the oscillator must be removed from the aircraft and kept powered up inside the hangar between flights.

To time tag the data records accurately there must be a time register driven by the time standard that has sufficient resolution to meet the computational requirements for the gravity system and that is long enough to provide an unambiguous time. The process of calculating gravity involves taking the second derivative of altitude with respect to time (i.e., to find vertical acceleration). This is an inherently noisy process, therefore the time should be reasonably precise. It has been found that a resolution of .1 ms is good enough for this purpose. A 32-bit register counting at a 10 kHz rate will count for over 119 h before overflowing. Since this is much longer than a survey flight, a 32-bit register is sufficient for time tagging purposes. This register must be available for any of the subsystems to interrogate when they have completed a data record.

Computer System

Existing data logging systems could probably acquire and log the data for the gravity system, but none has been found that will also allow on-line monitoring of the performance of the system. A computer system is needed to do all of the tasks. The selection of the computer system is based on data acquisition and logging requirements, real-time computing requirements, and on the physical aspects of size, weight, power consumption, and ruggedness.

The computer system and its interfaces to the subsystems of the gravity system must be able to handle both the formats of the data and the input rates of the data, while performing some calculations on the data.

GPS Data Requirements

The TI-4100 GPS receiver has a serial RS-232 compatible output. The data are binary and consist of various types of records. Records vary in length from 34 to 576 bytes, and consist of a record header and a record body. The user may choose which record types to receive; data are sent to the computer at 9600 baud. There is a handshake protocol between the computer and the GPS receiver, but it is nonstandard and therefore is not likely to be implemented as standard on any computer system.

The user will normally want only the User Solution records or the Relative Navigation records. These give, respectively, the position and velocity in earth-centered, earth-fixed coordinates or in local latitude, longitude, and altitude coordinates. The length of these blocks limits fix frequency to about 2/s. To use GPS interferometry techniques, the user must also record the Receiver Measurement records. This limits fix frequency to about 1/s.

To handle this input, the computer system needs an RS-232 interface that includes buffering. The operating system must be flexible enough to allow the user to write a device driver that will handle the protocol used by the TI-4100.

Inertial Navigation System Requirements

The Honeywell SPN/GEANS Inertial Navigation System has a serial output bus that puts out a series of data, including the current position and the velocity. The data on the bus are output at a 1 Mb/s rate. A special interface would have to be built to convert the serial data to parallel form. Since most of the data on the bus are not of interest to the gravity system, it may be advantageous to make the interface find only the data (position and velocity) that are needed. The computer would then need a general purpose parallel interface to read the data. The Litton LTN-72 also has a serial output bus that conforms to the ARINC 561 standard for aircraft navigation systems. The output bit rate is 5 kHz, and only the data desired such as latitude, longitude, track, and velocity are selected out of the data stream.

Gravity Data Requirements

The LaCoste-Romberg Gravity Meter has some 20 analog outputs and two digital outputs. Of these, 10 of the analog outputs and the two digital outputs are needed to calculate the local gravity field. Table 6 lists the gravity meter outputs that must be recorded. The Raw Beam signal should be sampled at about 10 Hz. The rest of the analog signals should be sampled at 1 Hz as should the digital values. The analog signals are in the -10 to +10 V range and should be sampled with a precision of 15 bits. A 15-bit A to D converter that can multiplex at least 11 channels (see pressure sensor description below) is required to satisfy the analog signal requirements. The digital signals are the output from shaft encoders and require an interface that converts the shaft encoder outputs to binary-coded-decimal form for input to the computer system. A general purpose parallel digital interface is needed on the computer system to read these data.

Table 6 — Analog Gravity Signals

1.	Average Beam
2.	Total Cross Coupling
3.	Total Correction
4.	Vertical Acceleration
5.	Average Cross Acceleration
6.	Average Longitudinal Acceleration
7.	Cross Acceleration
8.	Longitudinal Acceleration
9.	Zero Calibration
10.	Raw Beam
11.	(Pressure sensor)

The Bell gravity meter has only a digital-parallel output. A simple 16-bit parallel port is required in the computer.

Altimeter Data Requirements

The radar altimeter produces a dc signal of 0 to 10 V that is proportional to the time between transmission of a pulse and the reception of the reflected pulse. A 15-bit A to D converter is needed to convert the data to digital form. To get a reasonably smooth altitude measurement, the radar altimeter is pulsed 10,000 times per second and averaged over 100 samples. Only the averaged values are saved, but the system must be able to continuously sample the radar signal at 10 kHz while calculating the averages in real time. This can be done either on an intelligent interface or in the computer. In general, it is advantageous to do this type of task on the interface so that the computer has sufficient time to store the data and do data monitoring calculations.

The pressure sensor used for calculating altimetry has a dc analog output that is proportional to pressure. It has a range of 0 to 10 V and should be read 10 times per second to a resolution of 1 mV. The same A to D converter used for the gravity meter signals can be used for this purpose.

Miscellaneous Considerations

The data acquisition system must be able to time tag all input records to an accuracy of 100 μ s. To process the data, the processing programs must be able to determine the time when each item of data arrived to within 100 μ s. This is usually done by attaching an accurate time to each record, and then deriving the time for each data item within the record by making assumptions about sample rates. Thus it is important that the clock being used to tag the records is accurate and is tied to the various frequencies that are being used to determine sample rates on each of the data types.

While the primary task of the computer system is to collect and save data needed to calculate gravity, it is very useful to be able to monitor the quality of the data as it is being acquired. The methods currently being used to calculate gravity do not allow real-time monitoring of the final gravity values, but an approximate gravity value can be estimated in real time and displayed along with position, velocity, altitude, and some of the important inputs to the gravity calculation. The programs needed to monitor the system can be written in Fortran 77 and can run simultaneously with the data acquisition and logging programs.

The computer operating system should be intended for real-time operation; it should be based on an interrupt-driven structure and should allow for multiprogramming and multitasking. It should have good program development software including a Fortran 77 compiler, an assembler, a text editor, and a linker. The operating system should be relatively open, so that the user can write special purpose I/O drivers. Since airborne gravity is still in the early stages of its development, the computer system should be flexible and easy to work with so that changes can be relatively easy to implement.

The temperature control, power stability, and vibration of aircraft present a difficult environment and potential problem areas for the operation of a computer system. Most commercial computers operate over the temperature ranges existent on aircraft, but problems may occur during ground testing of the system when the aircraft may be particularly hot or cold. The computer should not require more power than can be supplied by the 400 to 60 Hz inverters used in the system. This is usually not a serious problem, although some disk drives may use extra power during spin up. Hewlett Packard computers have been found to operate well in the vibration environment of the aircraft because of the construction methods that include the use of relatively small boards that are well secured to the chassis, a good choice of connectors, and internal and external cabling that is well secured.

The NRL Data Acquisition System

The AGMS designed at NRL uses a Hewlett Packard HP1000 F-Series computer to run the RTE-6VM operating system. Figure 11 is a block diagram of this system. Some of the data acquisition task is off-loaded onto an interface built at NRL (described in the next section) that buffers up to four channels of data to avoid data loss. This interface has several circuit boards that can be plugged into it to perform different tasks. One of the boards reads the radar altimeter and averages the values. The averaged values and a count indicating when the average was completed are sent to the computer. One interface channel is used to read the analog and digital gravity meter outputs as well as the pressure altimeter. A third interface can be used to read the Litton 72 Inertial Navigator output that is ARINC standard 561. Optionally, a fourth interface is used to read a Litton 211 Omega receiver. This also uses the ARINC 561 standard. This method allows continuous data to be taken (i.e., no data loss) over the length of a flight, while at the same time a separate program can be run to estimate the current gravity field and to show the current state of the system. The data in the NRL interface memory are read into the computer through an HP12566A general-purpose 16-bit interface.

The GPS receiver is an early TI model that has a 16-bit digital output. This is read into the computer through an HP12930A 16-bit parallel interface. Data from all sources are stored on a Bering 7070 Winchester disk by the computer system. The disk has about 60 mega bytes (MB) of fixed memory and 10 MB of removable memory. The data are periodically printed on the HP Thinkjet printer. The monitor program displays the current state of the system on the HP2648 graphic terminal. An update is made about every 5 to 10 s. The monitor program will be described in the follow-on software report.

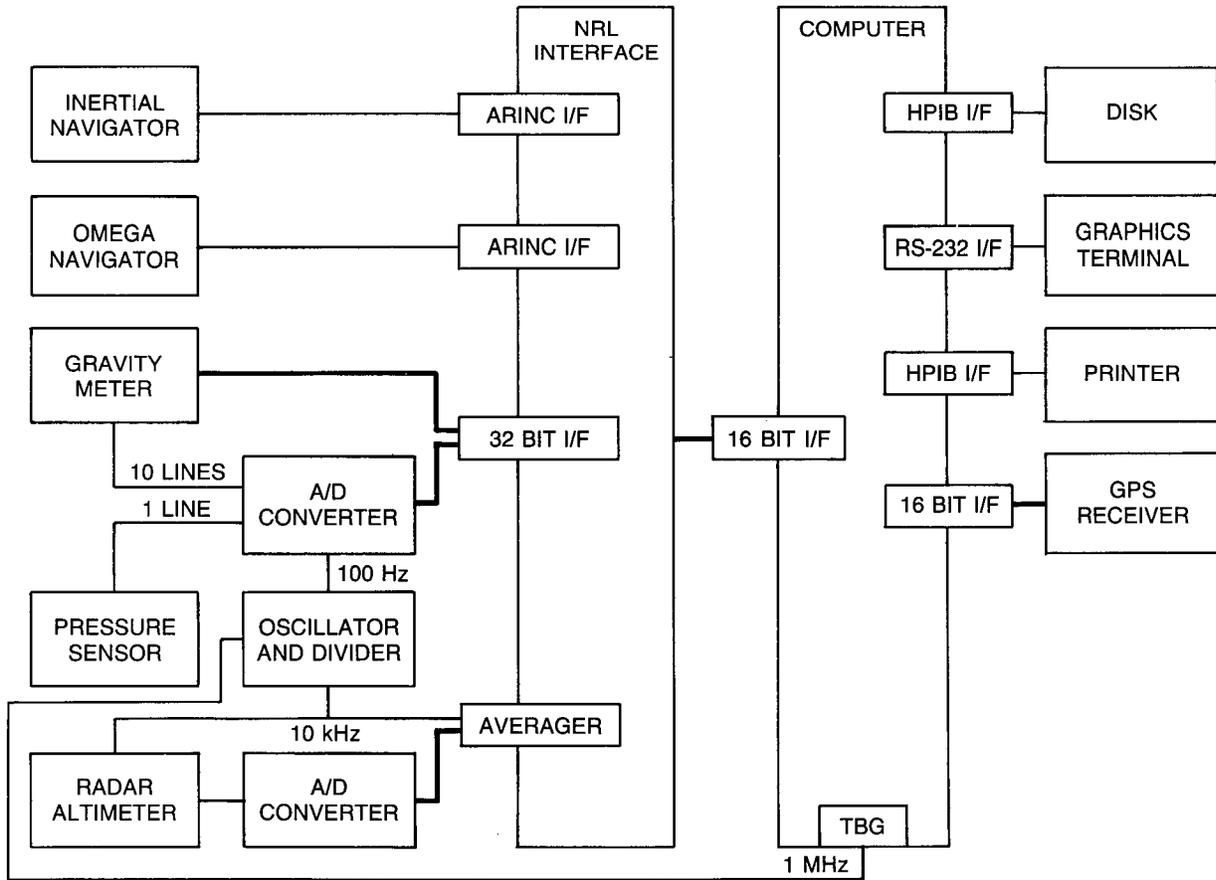


Fig. 11 – Block diagram of the NRL AGMS

The NRL Interface System

An interface system is required to process data from a variety of sensors and instruments, and to present this data to a computer for further processing. Also, the interface system acts as a buffer to relieve the computer from the burden of intensive I/O processing.

The measurement and collection of gravity data includes a variety of ancillary parameters that must be collected. They include:

- radar altitude measurements,
- atmospheric static pressure,
- position information from INS and Omega systems,

and other parameters such as aircraft motion, gravity meter error signals required in the calculation of gravity, and time information for tagging of data. The system should include input processing subsystems to modify the form of the input data and to configure the result into a computer compatible word. The system should also include sufficient storage buffers on each channel to simplify the CPU I/O requirements. The third requirement for the interface system is a subsystem used to communicate with the CPU for orderly transfer of data from each memory storage area.

Time synchronization of all parts of the system is an additional requirement for data acquisition and to simplify time-tagging of data. For the latter requirement, a highly stable clock is used. The clock is subdivided into different clock rates to meet the clocking requirements of the various subsystems. Figure 12 shows a block diagram of the timing system. The clock is obtained from an atomic

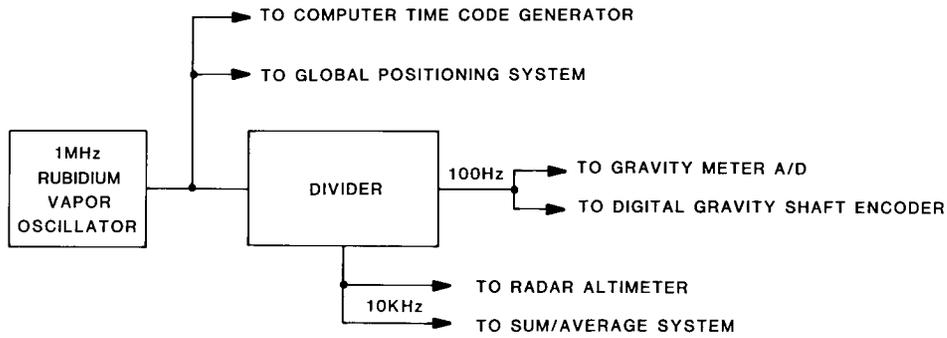


Fig. 12 — Block diagram of the NRL Data Timing Subsystem

cesium or rubidium frequency standard oscillator. It can be used as an input to a Global Positioning Navigation System and as an input to a dividing network to obtain different clock rates required by the computer for its Time Code Generator and by the Data Acquisition System for data manipulation.

Figure 13 shows a block diagram of the NRL Interface System for gravity studies from an aircraft. The system has four input channels but can be easily expanded to as many channels as may be required. Also, multiplexing A/D converters and multiplexing digital systems may be used for preprocessing of input data so that many more channels can be accommodated. The data can be manipulated, buffered, and transferred to the computer under control of a Direct Memory Access (DMA) System requiring minimum CPU intervention.

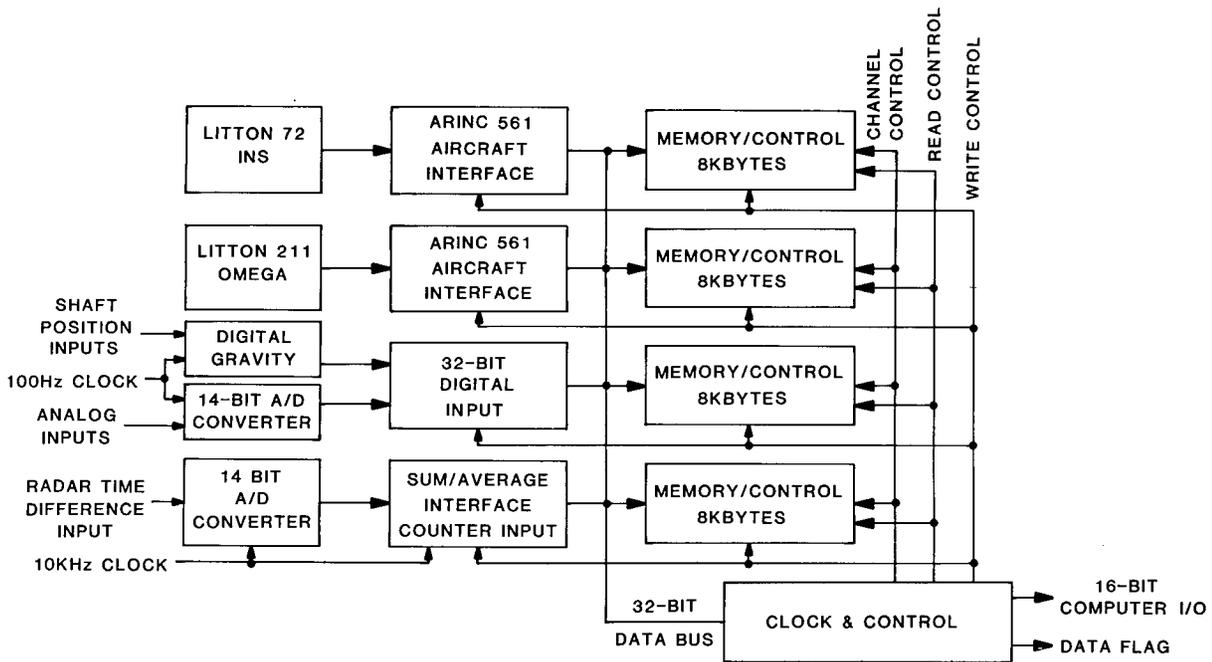


Fig. 13 — Block diagram of the NRL 4-channel interface

The Data Acquisition System is controlled by a 16 MHz internal clock that generates READ/WRITE timing signals for each channel. The timing signals are time-division multiplexed for control of each individual input as well as of the output to the computer. This clock also generates the necessary timing pulses required by the memory integrated circuits (ICs) for read and write operations. Each channel can receive 32-bit data at a rate of about 62 kHz independent of the rates of the other channels. The only constraint is the rate of transfer of data to the computer. This word rate is presently 125 kHz but can be easily increased by simple jumper changes.

As shown in the block diagram, the first two channels process data that come in the form defined by ARINC Specification 561.11 for aircraft systems. This includes three serial lines comprising clock, sync, and data signals. The electronics combine the three signals to generate a 32-bit word consisting of 8 bits of word identification and 24 bits of data. The first channel converts the signals from a Litton-72 Inertial Navigation System, while the second channel performs the same translation for a Litton-211 Omega Navigation System.

On all channels, the data are stored in memory as 32-bit words. When requested, these words are passed on to the Computer Interface Electronics and are transferred to the computer under DMA control as 16-bit words. The memory includes both read and write address counters. The Read Counter records the location in memory of the next data point that must be read, and increments after each read. The Write counter increments after each word has been written and keeps track of the location for the next write operation. A third counter, identified as a Status counter, is included and it records the difference between the Read and Write counters to indicate the number of double words available for transfer to the computer. This counter increments after each write operation and decrements after each read operation. Its value is used by the computer to determine the number of words that can be transferred under DMA control.

The third channel combines the encoded words from two mechanical counters displaying six digits of gravity and six digits of spring tension, with the output of a multiplexing A/D. The A/D is used to digitize the analog signals from the Gravity Meter (see Table 6). The digital signals and the digitized analog signals are strobed with the 100 Hz clock signal. One digit of the encoded signal combined with one channel of A/D converted input to form each 32-bit word is transferred to memory.

The fourth channel processes the radar altimeter's time difference measurements by summing a preselected number of readings and then dividing them by the number of readings and thus obtain an average that is combined with the output of a 16-bit counter to form a 32-bit word for storage in memory. The counter input is the same clock pulse used by the radar to generate its PRF. The counter reading is included to make sure that the correct number of pulses have been received and averaged.

Clock and Control Subsystem

All timing for the control of data by the NRL Interface System is performed by the Clock and Control System. A time-division multiplexing scheme is used to minimize interference between channels and between read and write operations. Figure 14 shows a block diagram of this system. The clocking system consists of a 16 MHz crystal-controlled oscillator subdivided into 16 unique time periods. Each period defines the time when one unique operation is to be performed by one of the four interface inputs or the one interface output. The interface output is used to control the transfer of data to the computer. The electronics in each slot may use the WRITE CLOCK to write into its memory, and then followed by the WRITE RESET CLOCK to reset and prepare the system for the next operation. The electronics perform a read function during the assigned READ CLOCK and READ RESET CLOCK time periods.

The clocking system generates all necessary timing signals required by the memory system to perform read and write operations. Only one set of timing pulses is required, since only one read or write function can be performed at any particular time. Therefore, these signals are connected to all memory systems.

This system performs also a second major function, the transfer of data between the interface system and the computer. The computer can request that a system be reset or that a system respond with a status word indicating the number of 32-bit words that are stored in memory and have not been read. The status word also includes an overflow bit, which indicates that the memory is full and that data are being overwritten. The application program is designed to request periodically the reading of data to avoid an overflow. An applications program controls the transfer of data to the computer. A control

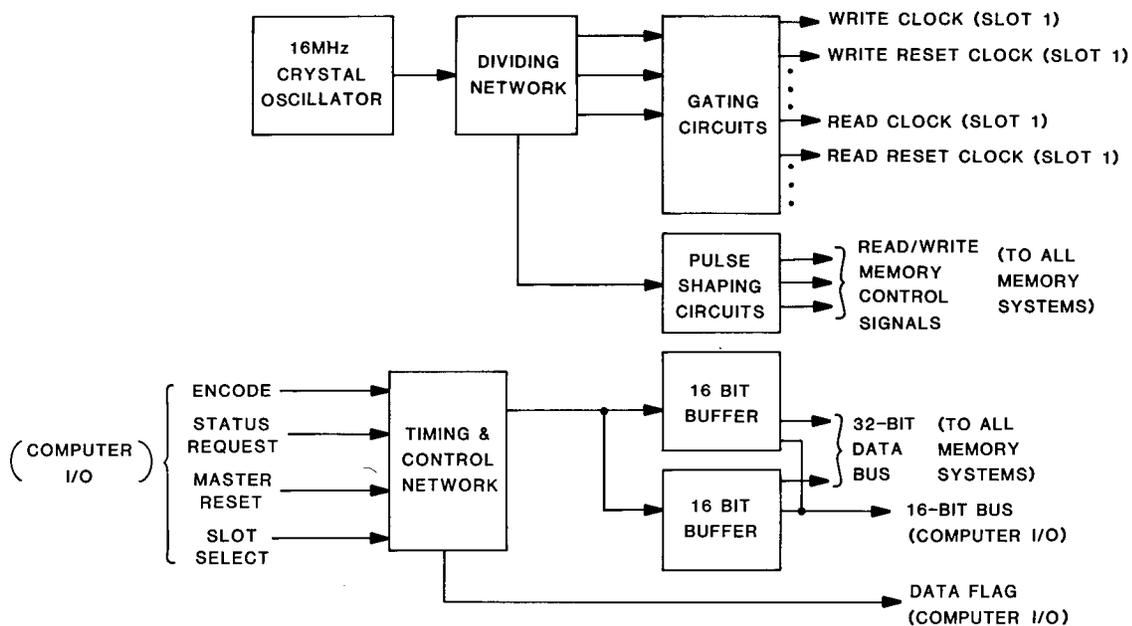


Fig. 14 — Block diagram of the Clock and Control Subsystem of the NRL Interface System

word is sent to the interface where two of the bits define a slot position, another bit defines a status request, and a fourth bit defines whether the request is a master reset of all the electronics for the selected slot. The ENCODE signal, when set, indicates that the computer has sent a request and a response is expected. When data are to be read, a request for the status word is made, which indicates to the computer the number of words available. This number is then used by DMA to determine the data block that will be transferred. An ENCODE and two bits of slot-select-code begin the transfer of data. The timing and control network reads a double word from requested memory and transfers this data, a 16-bit word at a time, to the computer. The transfer is accomplished by placing the word on the 16-bit I/O lines and strobing the data with DATA FLAG. This stores the data in the I/O buffer located on the computer I/O card, sets an Interrupt Request Flip Flop (F/F), and resets the F/F storing the ENCODE signal. When the computer services the interrupt, it resets the ENCODE F/F and the second 16 bit word is transferred. At the next ENCODE signal, the Timing and Control Network requests the next double word from memory. The transfer process continues at a rate of about 125 kHz until DMA receives a full block of data.

Memory and Control Subsystem

The NRL Interface System has one memory system for each of the four channels. Figure 15 shows a block diagram of this system. A memory system consists of read and write address counters and a status counter that tracks the number of 32-bit data words stored in memory that need to be read. A number of request flip flops are also included to indicate a pending request that needs to be serviced when the appropriate timing signals arrive. Memory modules are included to allow storage of up to 2048 32-bit words.

ARINC 561 Aircraft Interface

The ARINC 561 Specification for aircraft navigation systems defines the characteristics of three signals. The first is a clock signal with a period of $91 +42 -22 \mu\text{s}$. The second is the data signal that also has a period of $91 +42 -22 \mu\text{s}$, and the third is word sync that defines the start of the 32-bit word, and the start and end of the 24-bits of data. The logic levels of all the signals vary from 0 to +12 V.

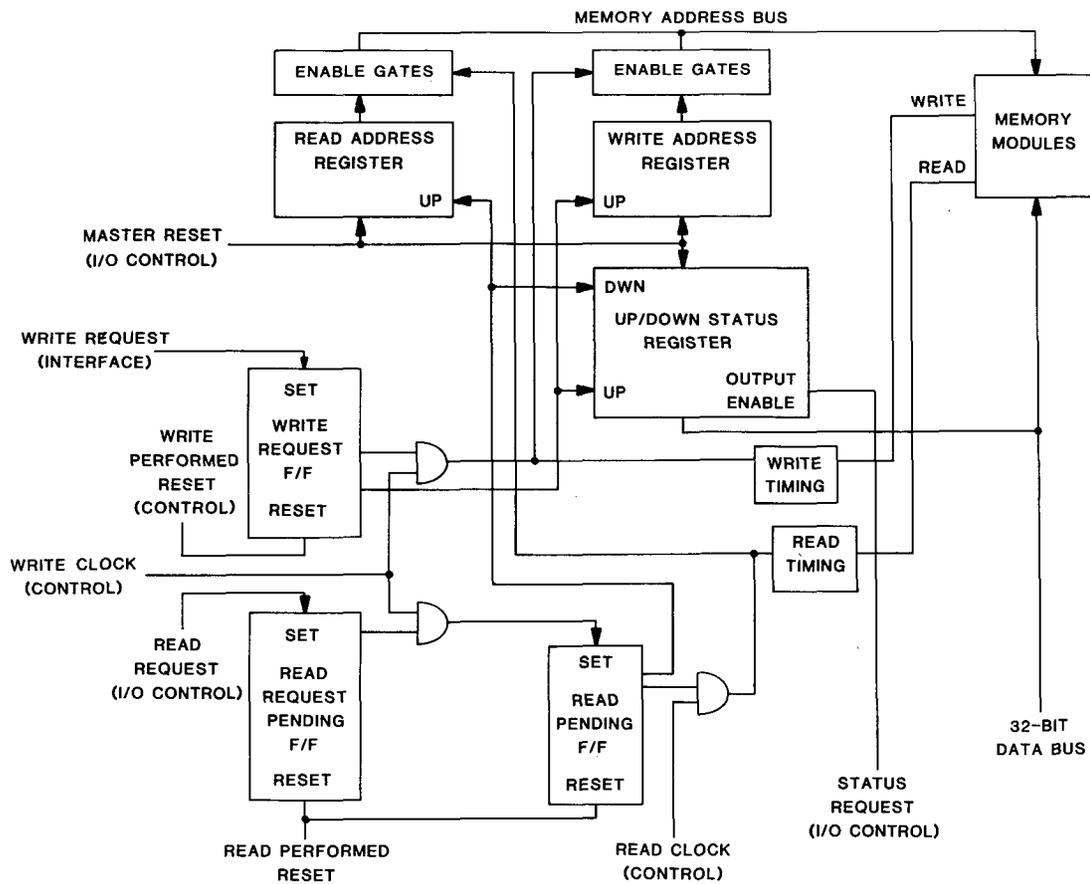


Fig. 15 — Block diagram of the Memory and Control Subsystem of the NRL Interface System

Figure 16 shows a block diagram of this system. Three level translators are included to change the +12 V differential inputs to +5 V single ended and to make them TTL-compatible. The clock signal is used to strobe the data into a serial to parallel converter, and the word strobe is used to shift the contents of the converter into a buffer when the full 32-bit word has been shifted. The word strobe is also used to request that the word be written into memory. A flip flop is set when this request is made. Then the request is transferred to the memory system at the next READ CLOCK pulse for that slot. At the same time, the 32-bit word is strobed into a second buffer. On the next write period for this slot, a write operation is performed and a WRITE PERFORM trigger is generated that enables the output of the buffer and places the data on to the 32-bit bus where the data is then transferred to memory. After the transfer is completed, a WRITE PERFORMED pulse is used to reset the Write Request Pending F/F. The process of transferring words into memory is performed at a rate of about 62 kHz. The data rate for the Litton Navigation Systems in question is about 156 words/s and can easily be handled without data loss.

16/32 Bit Parallel Interface

The storage of 16 or 32-bit TTL-compatible data words are processed by this interface. A block diagram is shown in Fig. 17. When 16-bit data is to be stored, the interface packs two words together before a write to memory is requested. When 32-bit words are to be stored, the interface acts as a double buffer and interrogator to inform the memory system when the data are available. Clocking circuits control the sequences and storage of the pending write request. When the second strobe for 16-bit data is received, the data are strobed into the second half of the buffer and into the set input of the WRITE REQUEST PENDING F/F. At the next READ CLOCK period, the request is gated to the WRITE REQUEST F/F of the memory system where it is serviced during the next Write Clock period. After the write function is completed, a WRITE PERFORMED clock resets all the request F/Fs and the process repeats.

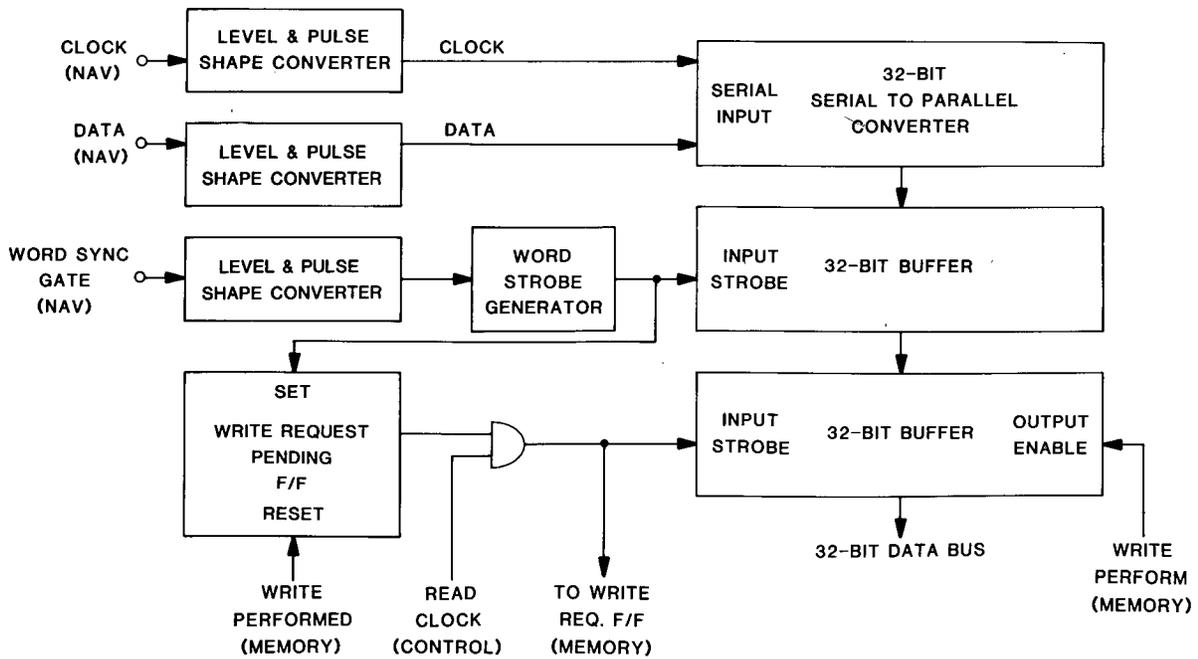


Fig. 16 — Block diagram of the ARINC 561 Interface

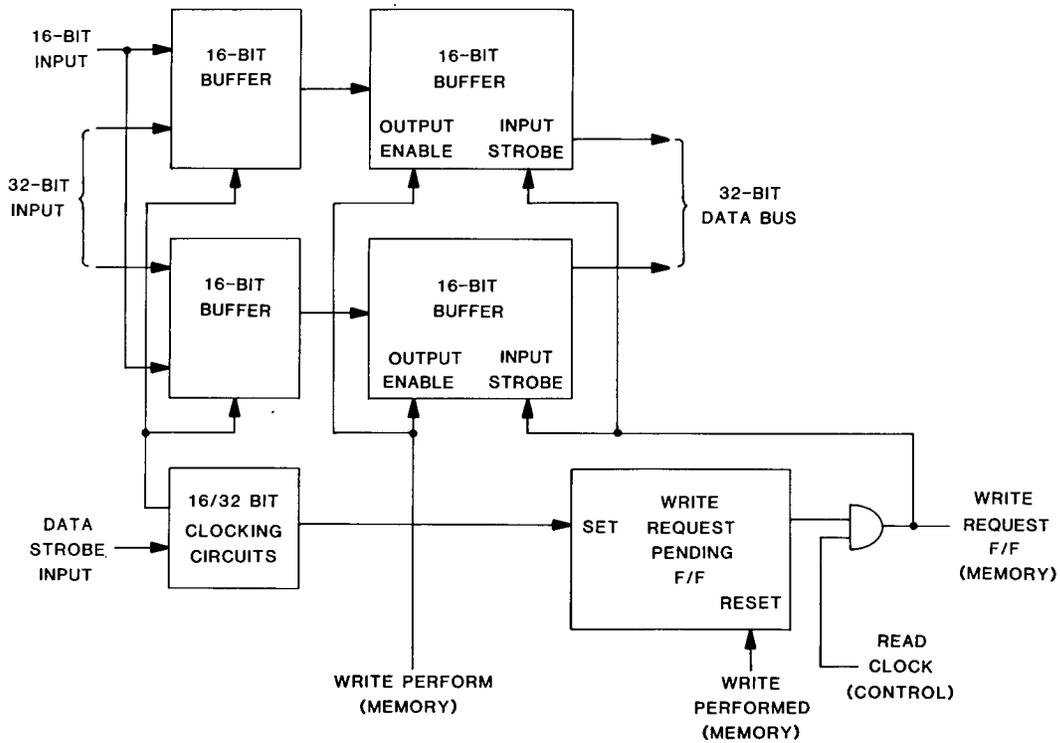


Fig. 17 — Block diagram of the 16/32-bit Parallel Interface Subsystem of the NRL Interface System

Digital Sum/Average Interface

The Digital Sum/Average interface is designed to sum a preselected number of 16-bit binary data and then divide this sum by the number of data points. The result is the data value that represents the average reading of the number of data points taken. Figure 18 shows a block diagram of the system. The system is designed around a 16 x 16 Multiplier/Accumulator Large Scale Integrated (LSI) chip. The peripheral circuits supporting the chip meet all the necessary timing, control, and buffering requirements.

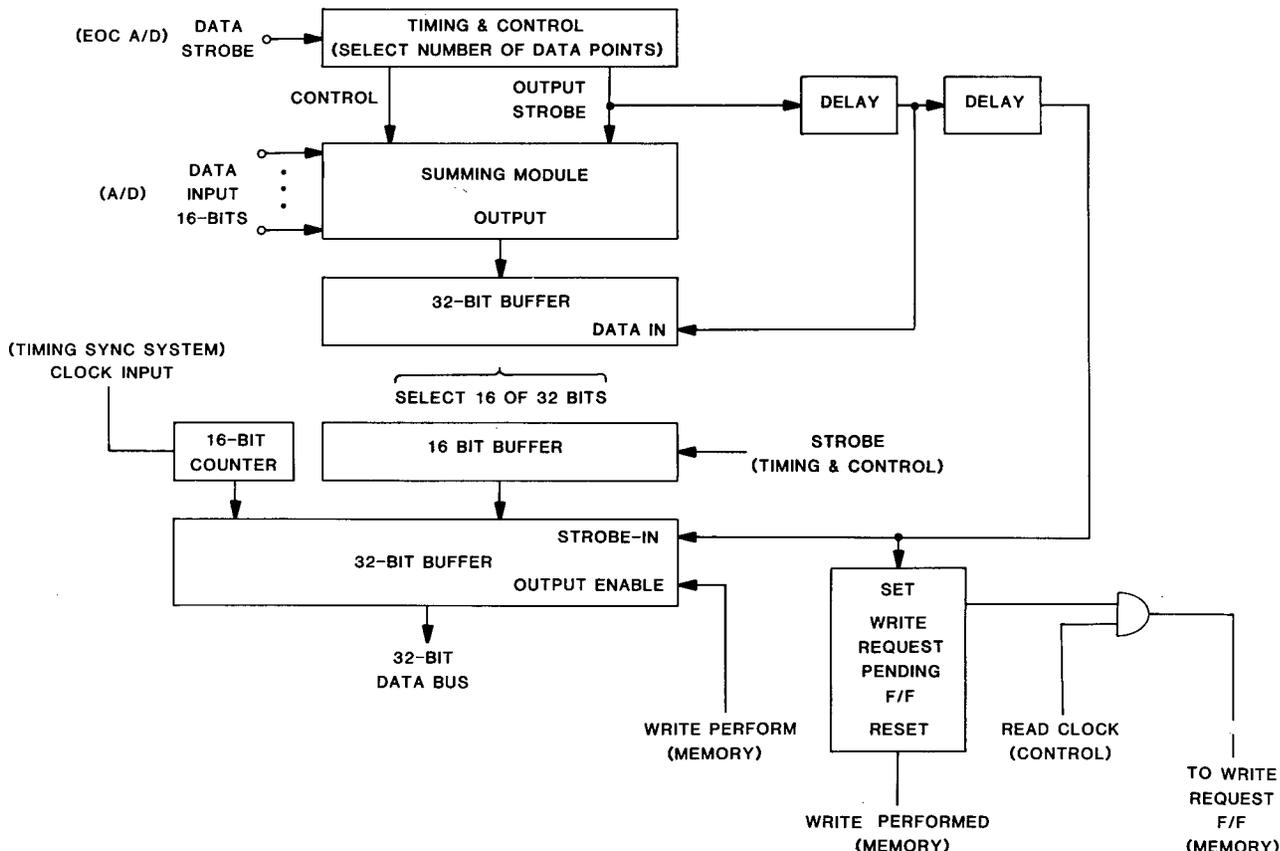


Fig. 18 — Block diagram of the Digital Sum/Average Interface for the radar altimeter

The timing requirements for the accumulator include three separate clock signals, data input and output strobes, and an accumulator reset that signals when the last data point is summed. Division by any power of 2 is accomplished by jumper selecting a timing signal from a 16-bit binary counter and by selecting the appropriate 16 bits out of a 32-bit binary sum. The 16-bit output is double buffered to minimize data loss.

This system is used by the radar altimeter to average a large number of returns. When a pulse is transmitted by the radar, a similar pulse is counted by a 16-bit binary counter located on the Digital/Sum Interface card. The count stored should correspond to the number of pulse returns that have been summed. When the counter indicates a larger number than was selected for summing, it indicates possible loss of some pulse returns. Both the averaged sum and the counter value are combined to give a 32-bit word that is then stored in memory. The strobe used for storing the data into the 32-bit buffer is also used to set a Write Request Pending F/F. On the next READ CLOCK for the slot, the ANDED signal is sent to the Memory System to set the WRITE REQUEST F/F. When the write is performed on the next WRITE CLOCK period, a WRITE RESET CLOCK follows and resets all the flip flops.

Power Distribution Subsystem

The NRL Interface System consists of four independent processing channels. An input or interface card and a memory card are associated with each channel. Also, the system includes a clock and control section located on two printed circuit cards. Therefore, ten card slots are used. The Power Distribution Subsystem shown in Fig. 19 is designed to furnish power to each slot through individual +5 V regulators. A single +9 Vdc power supply furnish the power for the regulators. Input and output filtering is included on all lines for maximum isolation between cards.

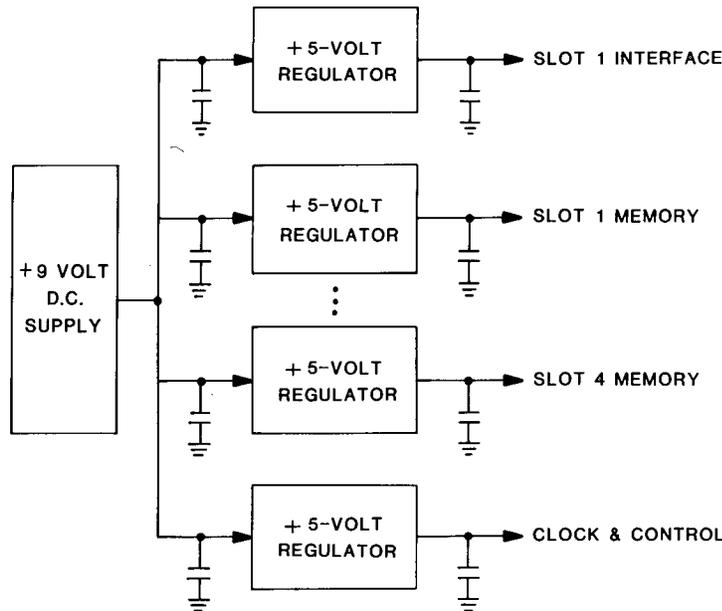


Fig. 19 — Power Distribution Subsystem for the NRL Interface System

Proposed Data Acquisition Systems

The proposed systems are based on the NRL system, but the equipment has been updated to current technology. The A900 is the current top of the line Hewlett Packard computer. This machine is about three times the speed of the F-Series computer and has the added advantage that all of its I/O channels can run in the DMA mode.

All data are stored on disk files, and the disk must be large enough to contain all the data necessary for one flight. Table 7 shows the approximate disk space required for each type of data. The table is based on the file structure being used on the NRL system and flights of no more than 12 h duration. The disk must also have space for the programs and operating system; therefore, a disk of at least 50 MB capacity is required. The HP7946A disk is recommended for this computer. It has 55.5 MB of memory and a cartridge tape that can hold up to 67 MB. At the end of each flight the data are archived on tape. This means that the facility that is used for processing the data must be able to read the cartridge tapes.

The data monitoring programs use the printer and the graphics terminal to show the status of the system in real-time. The terminal is also used to control the computer system. The printer is an HP2225D Thinkjet printer. This is a compact ink-jet printer that is not intended for heavy-duty usage but that is well matched to the requirements of the gravity system. The graphics terminal for this system is an HP2393A with 12 pages of local storage. A spare terminal is not necessary, but it is convenient as a system console and as a separate port for programmer access to the system. Both terminals the printer, and the GPS receiver can be connected to the computer through an HP12040C 8-channel RS-232 multiplexor.

Table 7 — Disk Space Requirements

Type of Data	Record Size (bytes)	Records/h	Bytes/h	Bytes/Flight
Gravity Meter	76	3600	273600	3283200
Radar Altimeter	420	3600	1512000	18144000
INS Navigation	48	3600	172800	2073600
GPS Position	54	5625	303750	3645000
GPS Velocity	61	1141	69601	835212
Total			2331751	27981012

The operating system for the A-series computers is RTE-A. It is similar to RTE-6VM and is well suited to real-time system implementation. The program development facilities for the operating system are excellent for a gravity system that is continually evolving with the technology.

The first proposed system, shown in Fig. 20, uses 16-bit parallel interfaces for input of most of the data. These can be either HP12006A boards or HP93799A boards. The difference is that the HP93799A has buffer memory on board that permits continuous data reading, but accurate tagging of the data with time is somewhat more difficult. If the LaCoste-Romberg gravity meter is used, then both analog and digital data must be read. If the Bell meter is used, then only the digital data must be read. The data from the radar altimeter can be read directly into the computer and averaged in the computer. This puts a fairly heavy computing load on the computer and it may be necessary to put a hardware averager between the analog to digital converter and the computer.

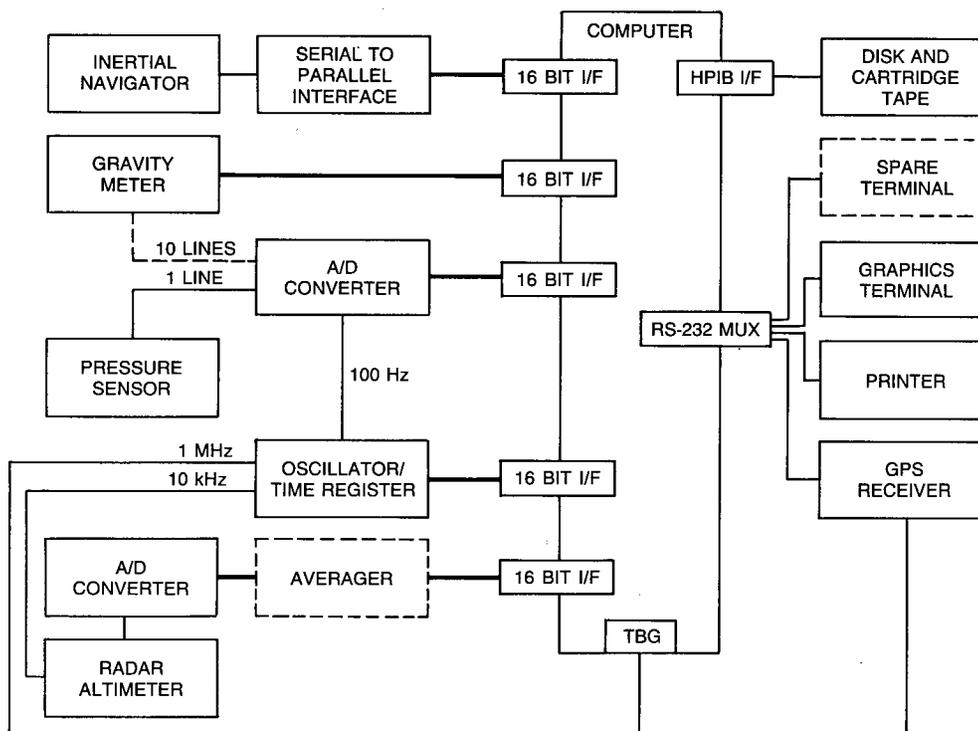


Fig. 20 — Block diagram of the proposed AGMS version 1. Dashed line from the gravity meter is required for the L&R but not for the BGM-3.

Also, some intelligent interfaces are available for A-Series computers. These I/O cards are fully programmable parallel interfaces that include buffer memory and microcomputers on the board. These programmable boards have the advantage of not requiring special built hardware. Therefore, because they are programmable, the system has the potential of being very flexible. On the other hand, the system development is difficult because software support for these boards is minimal.

Figure 21 shows the system configuration when HP14458A intelligent interfaces are used. Note that in this case the clock time register must be directly available to the intelligent interfaces as well as to the computer. This will allow each interface to attach an accurate time tag to each packet of data that it sends to the computer. The rest of the system remains the same as System 1.

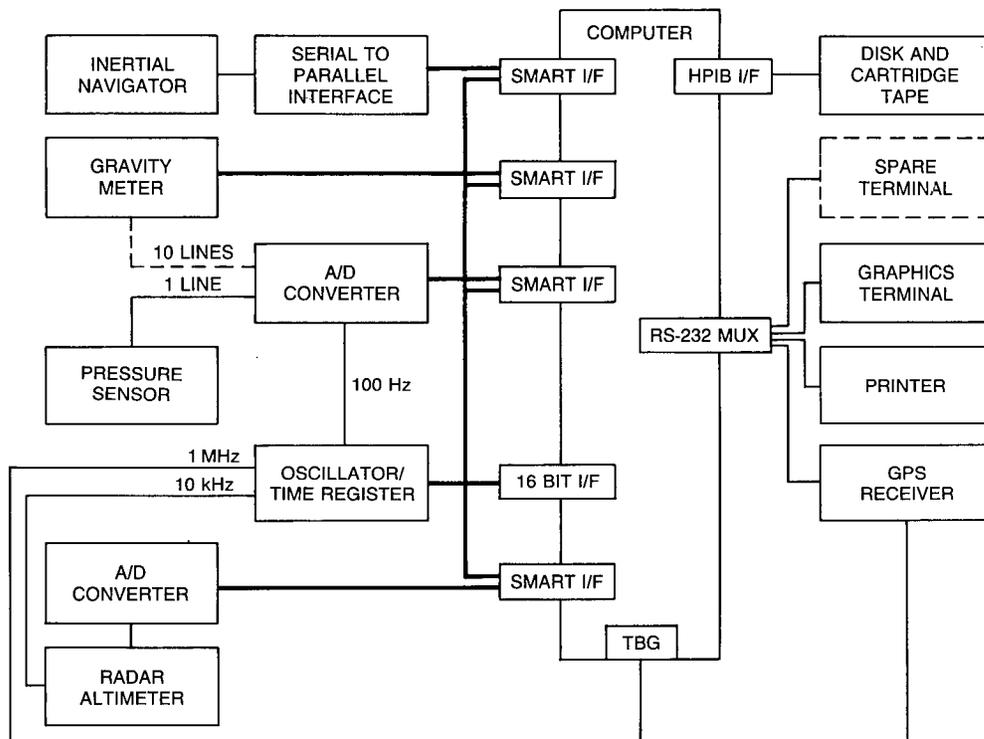


Fig. 21 — Block diagram of the proposed AGMS version 2 utilizing intelligent interfaces for the HP-A900 computer

The third proposed system, Fig. 22, is similar to the NRL system. The only differences are the type of gravity meter (either a LaCoste-Romberg or a Bell meter may be used), the GPS (the TI-4100 is used), and the computer and peripherals. The computer is an HP A900, and the peripherals are the same as in the first and second proposed systems. Note that the interface to the SPN/GEANS inertial navigator is not the same as the interface to the Litton 72, so a different front end interface board for the NRL interface would have to be built.

The major differences among the three proposed systems are a result of trading off software complexity for hardware complexity. The second proposed system is the simplest in terms of special hardware requirements, but it requires more complicated software. Software for this system must be developed for the computer and for the intelligent interfaces. Proposed system 3 simplifies the software, but it requires much more sophisticated special purpose hardware. Proposed system 1 is somewhere between the other two, but in this system it is more difficult to accurately tag the data with time. If the system is considered to be in the development stages (i.e., if it may be modified after some experience with it), then System 2 is probably the best of the three. Otherwise, System 1 is the recommended approach.

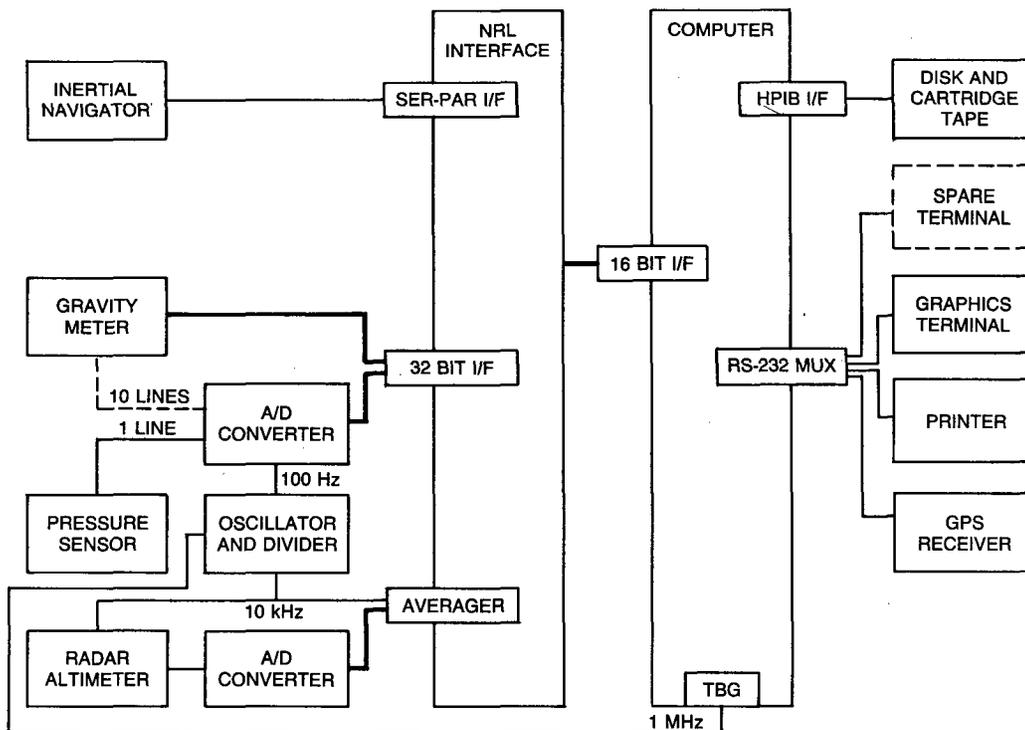


Fig. 22 — Block diagram of the proposed AGMS version 3

MISCELLANEOUS AIRCRAFT CONSIDERATIONS

Autopilot

One of the most important considerations in airborne gravimetry is the interaction of the autopilot/airframe system. The ability of the autopilot to damp out oscillation in the vertical and horizontal planes while flying close to the desired altitude and ground track is critical to successful measurement of gravity from aircraft. Our experience is with 2 Lockheed P3-A Orions equipped with the Bendix PB-20N Automatic Flight Control System (AFCS). This is a rather old technology (late 1950's), three-axis, electron tube, analog autopilot. It is prone to overheating and tends to oscillate in both planes at these times. Proper tuning of the autopilot for gain and damping is also important to minimize aircraft oscillation. When everything is operating well, the autopilot can fly the aircraft very precisely. It is impossible to hand-fly an aircraft like the P-3 as smoothly and accurately as a well-functioning autopilot.

One advantage of this unit is that the vertical channel can utilize the output from the APN-141 radar altimeter when operating below 1.5 km (5000 ft) and over water. This provides a long-wavelength correction to the autopilot for the variations in the heights of the isobaric surfaces. The pressure altitude is still used for the short period control of the aircraft altitude, but the radar effectively provides updates to the system. Without this provision the aircraft slowly climbs and descends along isobaric surfaces. These altitude variations can amount to several hundred feet over the length of a track. Since the radar altimeter unit described in section "Radar Altimeter" achieves some of its resolution by limiting the size of the vertical window, it is possible for the plane to climb or descend out of the valid data range. When this happens, it is necessary to adjust the window delay and in doing so a small amount of data can be lost. Some processing schemes also require that data over some survey region be acquired at a constant altitude for interpolation and estimation purposes. This would be difficult to accomplish without the input of an absolute altitude into the autopilot system.

The current operational Navy P-3C incorporates an updated AFCS, the AN/ASW-31, designed and built by Lear Siegler. This unit has several advantages over the PB-20N and one major disadvantage. There are two channels for each axis, roll, pitch, and yaw, that essentially provide total backup for increased reliability. The channel comparison circuitry also provides protection from transient impulses. The new AFCS is much better in handling turbulence, both in yaw and pitch. This improvement should significantly enhance the capability of the aircraft as a gravity measurement platform. The elevator channel incorporates a vertical accelerometer that is used to improve the response of the pitch attitude subloop of the altitude hold system. An integrated output of the accelerometer is also used to damp the phugoid oscillation of the aircraft. This reduction in the long period vertical motion of the aircraft should provide major improvement in the area that most affects gravimeter operation (see section "Gravity Meter"). Yaw damping is also increased through the use of sensitive lateral accelerometers and a yaw-rate gyro. Unfortunately however, the radar altitude hold mode was not included in the ASW-31. It relies strictly on the barometric pressure to maintain a fixed altitude. Variations in atmospheric pressure cause gradual (or not so gradual in the case of strong fronts) altitude changes as discussed in the previous paragraph. It may be possible to modify the ASW-31 altitude hold loop to include radar altitude information. If not, the AGMS radar altimeter should be modified to include an automatic range window shift.

The other function of an autopilot in the AGMS, besides flying as straight and level as possible, is to follow some predetermined track over the ground. The PB-20N, NRL's aircraft, includes a navigation coupler that uses information from an inertial navigation system to fly great circle routes between selected pairs of waypoints. There are two problems with this mode of operation. As mentioned in section "Gravity Meter", we have found that the use of this mode induces an increased amplitude in heading oscillation, and the INS accumulates position and velocity error with time. If the inertial is updated with a correct position from the GPS, the navigation coupler then causes the aircraft to change course and to fly direct to the next waypoint. This course change can cause a loss of several minutes of gravity data. Updates are therefore restricted to the start or end of data tracks. Rather than accept the increased heading oscillation, we operate the AFCS in a heading-hold mode with small course adjustments only as necessary to remain fairly close to the desired track. However, this is not an ideal situation.

The ultimate solution of flight control problems would probably be to design a new digital autopilot/navigation computer system. Virtually all the sensors needed are already in place for the AGMS. Sensitive gyros and accelerometers are installed on both the gravity meter and the inertial navigation unit. Very precise barometric and radar altimeters are being proposed for the AGMS. Nearly perfect real time navigation including heading could be available from the combination of the GPS and the inertial. However, autopilot design is not trivial and should be performed by experts in the field. A graceful failure mode is particularly important for low-altitude operations. The expense of such a design would be well worth the investment, as the autopilot could be optimized for the requirements of airborne gravity measurement leading to a reduction in overall system error and an increase in operational ease and reliability.

Electric Power Requirements

The equipment used for the NRL gravity studies (Table 8) includes units manufactured under acceptable commercial standards. The power required by most of these units is single phase 115 V at 60 Hz. Power available on the NRL P3 aircraft is at 400 Hz. Therefore, some form of conversion is necessary to furnish power to the measurement systems. Static Frequency Converters are units that perform this conversion very efficiently. Units designed to meet military standards are readily available and have historically shown reliable operation over many years of use.

The converter used by NRL on all their aircraft is the Unitron Model PS-62-66D. It operates with a three phase input of 200 V rms line-to-line between 360 and 440 Hz. The output is a voltage of 115 ± 3 V at 60 ± 0.6 Hz under all specified load, line, and temperature variations. It is capable of furnishing up to 3500 VA and is protected for overload and short circuit conditions. Full output is furnished over a temperature of -55° C to $+71^{\circ}$ C and up to an operating cabin altitude of 4.6 km (15,000 ft).

Table 8 — Equipment Power Consumption

Item	Power Consumption (W)
HP 1000 F-Series Computer	970
HP 2199C (A900) Computer	700
HP I/O Cards	
HP 12040B Async Multiplexer	15
HP 12006A 16-bit Parallel	15
HP 12009A HPIB	15
HP 12005A Async Serial	15
HP 12566B Microcircuit	5
HP 12821A HS HPIB	17
HP 12930A TTL	10
HP 12966A Async Serial	18
HP 59310B HPIB	15
HP 93790A GPIO Controller	15
HP 5065A Clock and NRL Dividers	75
HP 2225 Think Jet Printer	17
HP 7907 Disc Drive	145
HP 7946A Disc Drive	700
HP 2393 Graphics Terminal	100
HP 2648 Graphics Terminal	214
Bering 8170 Disc Drive	120
TI 4100 GPS (28Vdc Power)	
LaCoste & Romberg Gravity Meter	2000
Bell Gravity Meter	360
Honeywell YG8824A1 INS (400 Hz Power)	
NRL Interface System	125
NRL Oscillator and Divider	15
NRL Serial to Parallel Interface	5
Rosemount 1201F1 Pressure Sens.	5
Litton INS (400 Hz Power)	
Litton Omega (400 Hz Power)	

Table 9 shows the power and air-conditioning requirements for the three systems discussed. In all cases the power is 110Vac, 60 Hz, Single Phase, and is obtained from two Unitron PS-62-66D Static Frequency Converters.

Table 9 — Power and Air-Conditioning Requirements

System	Power (with L/R) (W)	A/C Req. (BTU)	Power (with Bell) (W)	A/C Req. (BTU)
NRL Gravity System	4427	15123		
Proposed System (Fig. 2)	4648	15878	3008	10275
Proposed System (Fig. 3)	4643	15860	3003	10258

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